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PALEONTOLOGY



GEOLOGY OF THE ARABIAN PENINSULA

Yemen

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Geology of the Arabian Peninsula Yemen

By F. GEUKENS

Translated from the French by S. D. BOWERS

GEOLOGICAL SURVEY PROFESSIONAL PAPER 560-B

*A review of the geology of Yemen as shown on
USGS Miscellaneous Geologic Investigations
Map I-270A, "Geologic Map of the Arabian
Peninsula," 1963*



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FOREWORD

This volume, "*The Geology of the Arabian Peninsula*," is a logical consequence of the geographic and geologic mapping project of the Arabian Peninsula, a cooperative venture between the Kingdom of Saudi Arabia and the Government of the United States. The Arabian-American Oil Co. and the U.S. Geological Survey did the fieldwork within the Kingdom of Saudi Arabia, and, with the approval of the governments of neighboring countries, a number of other oil companies contributed additional mapping to complete the coverage of the whole of the Arabian Peninsula. So far as we are aware, this is a unique experiment in geological cooperation among several governments, petroleum companies, and individuals.

The plan for a cooperative mapping project was originally conceived in July 1953 by the late William E. Wrather, then Director of the U.S. Geological Survey, the late James Terry Duce, then Vice President of Aramco, and the late E. L. deGolyer. George Wadsworth, then U.S. Ambassador to Saudi Arabia, and Sheikh Abdullah Sulaiman, then Minister of Finance of the Government of Saudi Arabia, lent their support to the plan. In November of the following year, 1954, Director Wrather approved the U.S. Geological Survey's participation and designated G. F. Brown responsible for the western Arabian shield region in which he had previously worked under U.S. foreign-aid programs. In January 1955 F. A. Davies, Chairman, Board of Directors, Arabian-American Oil Co., approved Aramco's participation and appointed the late R. A. Bramkamp, chief geologist, responsible for compilation of the area within the Kingdom where the sediments crop out. This responsibility fell to L. F. Ramirez following the death of R. A. Bramkamp in September 1958.

R. A. Bramkamp and G. F. Brown met in New York in February 1955 and planned the program, including scales of maps, areas of responsibility, types of terrain representation, and bilingual names. Thus there was established a cooperative agreement between the Kingdom of Saudi Arabia, the U.S. Department of State, and the Arabian-American Oil Co. to make available the basic areal geology as mapped by Aramco and the U.S. Geological Survey.

The agreement specified publication of a series of 21 maps on a scale of 1:500,000, each map covering an area 3° of longitude and 4° of latitude. Separate geologic and geographic versions were to be printed for each of the quadrangles; both versions were to be bilingual—in Arabic and English. A peninsular geologic map on a scale of 1:2,000,000 was to conclude the project.

High-altitude photography, on a scale of 1:60,000, of the Kingdom of Saudi Arabia was initiated during 1949 by the Aero Service Corp. and completed in 1959. Both third-order vertical and horizontal control and shoran were utilized in compiling the photography. This controlled photography resulted in highly accurate geographic maps at the publication scale which then served as a base for the geologic overlay. The topography of the sedimentary areas was depicted by hachuring and that of the shield region by shaded relief utilizing the airbrush technique.

The first geographic quadrangle was published in July 1956 and the last in September 1962. While preparation of the geographic sheets was in progress, a need arose for early publication of a 1:2,000,000-scale peninsular geographic map. Consequently, a preliminary edition was compiled and published in both English and Arabic in 1958. The second edition, containing additional photography and considerable new topographic and cultural data, was published in 1963. The first of the geologic map series was published in July 1956 and the final sheet in early 1964. The cooperative map project was completed in October 1963 with the publication of the 1:2,000,000-scale "Geologic Map of the Arabian Peninsula" (Miscellaneous Geologic Investigations Map I-270 A).

As work on the quadrangles progressed, geologists, companies, and governments working in areas adjacent to the Kingdom of Saudi Arabia were consulted by Aramco and invited to participate in the mapping project. The number of cooperating participants was expanded to 11, which included the operating oil companies in the peninsula and which are identified elsewhere in this text; the Overseas Geological Surveys, London; the Government of Jordan; F. Geukens, who had worked in Yemen; and Z. R. Beydoun, who had studied the Eastern Aden Protectorate. With the close cooperation of the authors, the new data were added to data already plotted on the base map of the Arabian Peninsula.

As the geological coverage of the peninsular map grew, the need for a text to accompany the map became apparent to both the U.S. Geological Survey and the Aramco geologists. Exploratory conversations were begun by Aramco with companies working in the other countries of the Arabian Peninsula for their participation in the preparation of a monograph on the geology of the Arabian Peninsula. Each author prepared a description of the geology of the area for which he was responsible, as shown in the sources of geologic compilation diagram on the peninsular map. The U.S. Geological Survey undertook the publishing of the volume as a professional paper, and the Government of Saudi Arabia was to finance its printing. It was early agreed that there would be no effort to confine the contributions to a standard format and that no attempt would be made to work out an overall correlation chart other than shown on the "Geologic Map of the Arabian Peninsula." Thus, the individual style of authors of several nationalities is preserved.

Cooperation and relations have been of the highest order in all phases of the work. The project would not have been possible without the full support of the U.S. Department of State, the Kingdom of Saudi Arabia, and all contributors. In fact, the funds which made publication of this volume possible were contributed by the Saudi Arabian Government.

The data provided by the maps and in the professional paper provide information for an orderly scientific and economic development of a subcontinent.

O. A. Seager

O. A. SEAGER,
Arabian-American Oil Co. (Retired).

W. D. Johnston, Jr.

W. D. JOHNSTON, JR.,
*Former Chief, Foreign Geology Branch,
U.S. Geological Survey.*

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GEOLOGY OF THE ARABIAN PENINSULA

YEMEN

By F. GEUKENS¹

English translation from the French by S. D. BOWERS²

ABSTRACT

After the leveling of the Precambrian metamorphic basement toward the end of the Paleozoic, sandy formations of continental facies were deposited mainly in the northern part of Yemen.

From the Liassic onward a zone of subsidence occurred in the central and northern areas. This zone was filled with fluviolacustrine sediments. It was only from the Late Jurassic on that a marine transgression covered the entire territory. The zone of subsidence remains, more accentuated toward the Red Sea.

During the Mesozoic, sandy conglomerates were deposited in the areas of subsidence.

The last marine transgression, of Paleocene age, involved the central part of the country.

INTRODUCTION

The southwestern part of the Arabian Peninsula, called "Arabia Felix" in the ancient literature, was long known as a mysterious and impenetrable country. Scientific exploration was limited to that done during a few journeys made by botanists, philologists, entomologists, and others.

Geological studies did not begin in Yemen until the 20th century, but geographical exploration dates from the 18th century with the travels (dearly paid for by his companions) of Niebuhr in 1763, who succeeded in crossing the area between Al Hudaydah, San'a, Ta'izz, and Al Mukhā. Much geographical information was acquired during the 19th century. The travels of Botta (1841) in 1836 and Passama in 1843, and the well documented journeys of archeologists Halévy from 1872 to 1879 and Glaser (1913) from 1885 to 1899 provided the foundation for future exploration.

The first regional topographic mapping was done by Beneyton (1913) for the purpose of constructing a railroad and branch line from Al Hudaydah to San'a. He mapped the borders of the triangular area between Ta'izz, San'a, and Zabid (Al Hudaydah). The first geological studies resulted from explorations by Botez (1912) along the Al Hudaydah-San'a route during the Turkish occupation. Petrographic material which he brought back was studied by Roman (1925), who prepared an extensive report. Lamare (1923a) crossed the southwestern and central parts of Yemen, where he gathered considerable geographic and geologic data and established a preliminary stratigraphic column.

Some years later, Rathjens and Wissmann (1929) obtained permission to conduct scientific research in the Al Hudaydah-San'a-Ta'izz area. They made four trips—in 1927-28, 1931, 1934, and 1937-38—and completed the studies started by Lamare.

Werdecker's (1939) geographical work and Scott's (1939) descriptions of his scientific journeys furnish supplementary information concerning the area traveled by their predecessors.

Geologists Fricke (1953), Lipparini (1954), and Karrenberg (1956) visited the country for economic geological study. The purpose of their investigations being limited, they deviated only slightly from the triangular route from Al Hudaydah to San'a to Ta'izz. Karrenberg was the first geologist to cover the Ta'izz-Ibb-San'a route by automobile.

In two journeys, 1953-54 and 1954-55, the author, as an expert under the technical assistance program of the United Nations, was able to travel through the country on a geological survey and visit previously unexplored regions, thanks to the cooperation of the United Nations Organization and the Government of Yemen (Geukens, 1960).

¹ Institut Géologique de l'Université de Louvain, Louvain, Belgium.

² Arabian American Oil Co., Dhahran, Saudi Arabia.

PHYSICAL GEOGRAPHY MORPHOLOGY

Yemen can be divided into three physiographic provinces: a maritime plain called At Tihāmāh bordering the Red Sea, a mountainous region drained by streams debouching into the Red Sea, and an interior undulating plateau in the east, between 1,500 and 2,500 meters in elevation, where drainage flows inland.

The maritime plain, 30 to 40 kilometers wide, is a sediment-filled part of the Red Sea graben. It consists of two parts, the limits of which are not precise and are, therefore, difficult to trace. One part, adjacent to the Red Sea, is composed of late Tertiary and Quaternary marine formations covered by Recent eolian deposits. The other part, toward the interior, consists of thick deltaic deposits related to numerous important wadis which disappear in the maritime plain. Numerous fresh-water springs are found near the border between the two parts.

The central mountain region occupies the west flank of a horst which lies between the Red Sea graben on the west and the Arabian desert on the east. The mountains are dissected by wadis characterized by strong headward erosion which is highly diversified depending on the composition of the bedrock. South of Wādī Lā'ah, from Jabal Shu'ayb through Jabal Dawrān and toward Ta'izz, the mountain region is incised by rivers (torrential during the rainy season) whose valleys progressively widen to the west. The many mountain massifs in this part are commonly secondary horsts. The terrain consists mostly of tuffs and compact lavas in horizontal attitude and explains the formation of steep ravines more than 1,500 to 2,000 m deep in several places. Near the outlets of the main wadis the valleys widen, and large stepped terraces alternate with moderately high hills. Near At Tihāmāh the western limit of the mountainous area is difficult to define because isolated hills emerge through the fluvialite deposits.

North of Wādī Lā'ah fluvialite erosion is more advanced and has cut into basement rock and sedimentary formations. Thick calcareous strata form very steep cliffs, chiefly in the upper courses of these wadis (Hajjah and Kublān areas).

In the interior, plateaus of various dimensions range from 1,500 to 2,500 m in elevation and are covered with either fluvialite, eolian, or volcanic deposits. They are separated only by low hills. The southern part of the San'a plain became a terrace by capture of the Wādī Wa'lān tributaries. In other places, the plateaus are cut by faults which form depressed areas and appear as alluvium-filled valleys—notably the plains of San'a 'Amrān, Al Ḥarf, Sa'dah, and others.

Generally, the interior plateaus grade without a sharp break into the more desert region to the east. This is illustrated in the northern part of the country where the Wādī al Jawf drops evenly to the desert. The area southeast of Jabal Maflūq is characterized by intrusive granitic mountains which rise above the calcareous plateau, and dense vegetation grows for some distance along the main wadis. Local silt and loam plains are commonly formed through deposition behind ancient artificial dams. The true desert region begins east of the horst formed by Jabal Haylān and Jabal Balaq. The transition in this area from plateau to desert is locally very abrupt. The upper channels of Wādī Adhanah and Wādī Raghwān show very active headward erosion by the sharp intensification of relief east of Jabal ash Sharafah (Tiyāl).

Contemporaneously with the subsidence of the Red Sea graben, young rivers brought large quantities of sediment. The subsurface of At Tihāmāh plain on the eastern side is formed of thick conglomeratic and other terrigenous deposits; on the western side, of salt, sand, shale and limestone.

At the end of the Pleistocene, tributaries to the Red Sea captured many tributaries of the rivers flowing toward the interior of the country. The capture as well as the decrease of rainfall during the Holocene explains the presence of gravelly fluvialite deposits standing out in relief in the desert region to the east, the surrounding sand having been removed by the wind.

METEOROLOGY

Precipitation in Yemen is strongly influenced by relief and consequently varies considerably from place to place. Meteorological observations were made by J. E. Hansen, engineer, and Dr. Carlo Toffolon, then personal physician to the Imam, at San'a and Ta'izz from 1942 to 1944. According to their observations at Ta'izz, the number of rains ranges from 90 to 160 per year, and annual precipitation ranges from 450 to 700 millimeters. Rainfall may exceed 50 mm in a single torrential shower. Two rainy periods are distinguished at Ta'izz: (1) the most important period, in which precipitation may exceed 600 mm, extends from April to May, or in some years to June, and (2) a shorter period in which rain falls mostly during August and September. West winds predominate during the rainy seasons.

At San'a annual precipitation ranges from 200 to 500 mm (60 to 90 showers) and also falls largely within two periods: (1) April to May and (2), the most important, from the latter part of July through the first half of August. Clouds generally gather on the west slopes of the main massifs and cause very heavy rainfall which accounts for the erosive action of the

wadis, the fertility of the land, and the number of local springs.

GENERAL SKETCH OF GEOLOGIC HISTORY

Schistose formations cut by masses of Precambrian granite crop out mainly in the east, north, and north-west parts of the country as well as in some isolated horsts. Preliminary study of these areas did not lead to an adequate mappable subdivision.

The formations have undergone regional metamorphism and intense folding in a general north-south direction. During this period important granitic massifs were emplaced. Precambrian formations oriented east to west were observed only in isolated places, a condition which did not allow establishment of structurally differentiated units.

During a continental period of long duration, erosion converted the region to a Precambrian steppe plain. Paleozoic transgression (Cambrian through Silurian?) probably extended over the area. Folding is indicated by a few remains of almost vertically inclined dark shales.

In another long continental period that followed, erosion almost completely removed the Paleozoic formations and created a perfect peneplain on which a very leached almost entirely quartz soil developed. At the end of the Paleozoic, or Permian, the peneplain was warped and the old surface was eroded in the south and redeposited as a delta or as dunes in the north (Wajid Sandstone). The beginning of the Mesozoic was characterized by a warm climate in which secondary basins formed in northeast Yemen. These basins were filled by continental red sandstones, indicating the nearness and influence of the landmass. Deposition of dark-green and gray-black shales of fluviolacustrine origin (Kohlan Series) followed. In isolated bays or near the coast short periods of emergence resulted in the formation of gypsum lenses.

During the Malin, the most important transgression extended over the entire country, and formed shallow-water calcareous deposits (Amran Series). Initially, the transgression followed along local depressions. An example of such a depression is northwest of San'a where Bathonian to Callovian carbonate rests on the Kohlan Series. To the north where the limestone is more chalky, the transgression was a little later (Callovian to Oxfordian). This area corresponded to the neritic zone containing stromatopora, and was separated from the great basin which extends into Saudi Arabia.

Commencing with the Oxfordian, the transgression covered the whole eastern and southern parts of the country. During this period subsidence zones formed in the desert area of Ramlat as Sab'atayn and in south-

west Yemen. In the central and southern parts of the country, Late Jurassic marine transgression took place directly on the Precambrian basement. (See fig. 1.)

A period of continental environment followed toward the end of the Late Jurassic. A lagoonal stage occurred in the center of the depressions, where gypsum and salt were deposited, while the margins of the basins emerged and were subjected to erosion. Continental sandy conglomerates of Cretaceous age (Tawilah Group) were laid down, probably over the entire area. The Tawilah Group is found wherever it is covered and protected by the overlying Trap Series. Tilting followed, along with greater deposition of sand in the flat-bottomed basins.

During the Paleocene a narrow sea spread over the center of the country; the neritic facies (Medj-zir Series) attests to the nearness of the landmass, where a tropical climate formed lateritic soil on its exposed surface.

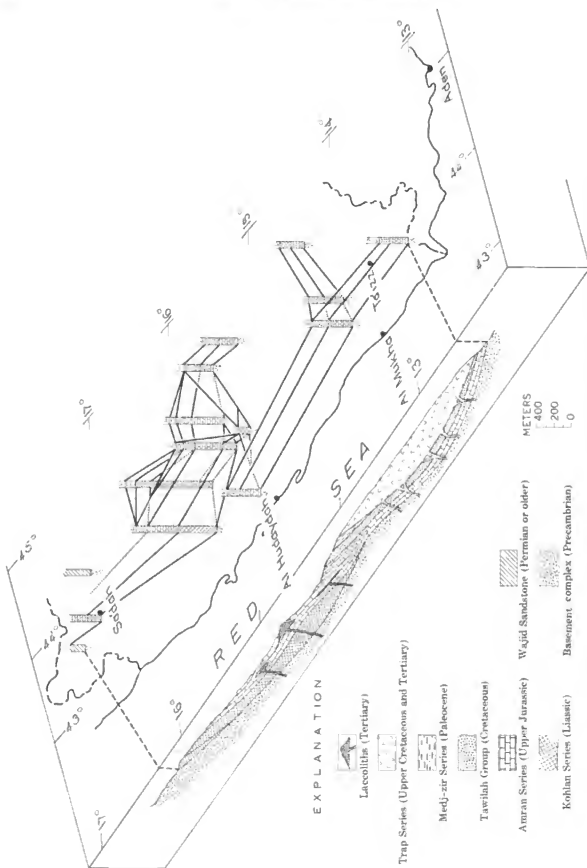
Tectonic movements, resulting in faulted domes, affected especially the central part of the country, where Jurassic and Cretaceous beds were removed by erosion at the beginning of the Tertiary.

Intense volcanic and intrusive activity began locally at the end of the Cretaceous and became widespread during most of the Tertiary. Volcanism is especially evident in southwestern Yemen where flows and tuffs locally exceed 1,500 m thickness (Trap Series); silicic laccolith intrusions are more common to the north. Calm intervals during the Oligocene and Miocene produced fluviolacustrine deposits intercalated with the Trap Series. Very intense tectonic activity characterized by normal faulting continued to the end of the Tertiary. Recent granitic intrusions penetrate the Trap Series, especially in the western part.

In the Quaternary, volcanic materials were sporadically distributed over the whole country; large areas of basalt flows and many craters characterize the central part of Yemen near San'a, Dhamar, and Ma'rib. Small basaltic craters are irregularly distributed over the entire territory.

Major loess deposits extend widely over the plateaus. Recent faults which facilitated erosion abruptly limit the areal extent of the loess fields.

Structural deformation has strongly modified the drainage pattern. Examples of very recent stream capture and indications of future capture are noted in the terrain, especially south of Ma'bad. Major terraces occur not only in the lower channels of the wadis but also in the upper channels of the Red Sea tributaries where the waters erode the old fluvialite deposits related to the wadis which flow eastward toward the interior of the country.



BASEMENT ROCKS

A complex, not yet subdivided, underlies all the subhorizontal sedimentary formations. It is composed of highly metamorphosed rocks enclosing large granitic massifs. The basement crops out mainly in the eastern and northern parts of Yemen, as well as in the bottoms of horsts which are uplifted through the Trap Series.

In the eastern part of the area of horsts north of Ta'izz, the basement consists mainly of mica schist (oriented generally north to south) and pink granite which has two micas and contains pegmatite and aplite veins. In the central part the granites contain large gneiss and mica-schist xenoliths, at places measuring several tens of meters in thickness.

The basement in the horst south of Bājil is likewise composed of gneiss and mica schist, as well as pink orthoclase granites.

The basement exposed south of Wādī Surdūd is composed of mica schists oriented east to west and dipping 45°S. In the Wādī Surdūd (fig. 2) farther north, granite exposures include large mica-schist xenoliths.

In the floor of Wādī Lā'ah north of Aṭ Tawīlah, the Precambrian is oriented N. 40° W. and dip is nearly vertical. It consists of chlorite schist, garnet schist, and gneissic quartzite. Several pegmatite veins, 20 to 50 centimeters thick, containing black tourmaline

crystals as much as 14 cm long, cut the basement. Downstream, the metamorphic series includes three granite massifs.

The anticline uplifted between Radā' and Širwāb in the southern part near the Aden Protectorate frontier is a highly folded complex oriented generally N. 10° E. The folds show very pronounced dip.

Farther north, in the upper channel of Wādī Adhanah, the basement is composed of gneiss, mica schist, and amphibolite. Nearly midway between Aḍ Dayq and Širwāb, the basement includes a conglomerate layer which appears to separate two different tectonic complexes.

In the Širwāb area the general orientation of the Precambrian is north to south. West of the town, gneiss and garnet schist crop out; to the east, gneiss and mica schist are exposed.

Toward Ma'rib, west of Jabal Balaq, mica schist, quartzite, and amphibolite (oriented north to south) are exposed. This great Precambrian dome plunges to the north near the upper channel of Wādī Raghwān.

Jabal Dakhan, 25 kilometers northwest of Širwāb, is a granite dome more than 5 km long. On the east and west slopes, the granite is covered by a thin quartzitic bed overlain by green chlorite schist which grades into gneiss and amphibolite within several meters

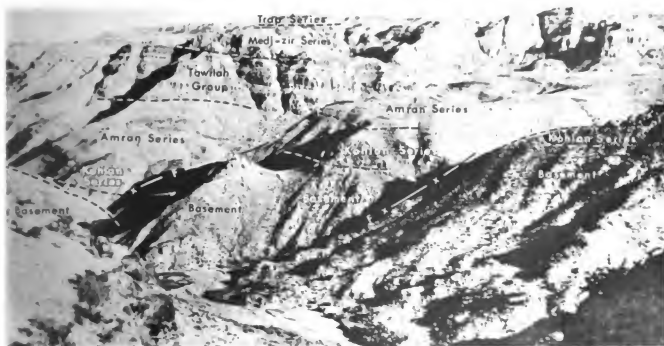


FIGURE 2.—Basement and sedimentary formations exposed in the upper course of Wādī Surdūd. F indicates fault.

East of Jabal Tiḡāl, the basement consists of gneiss and garnet schist overlain by quartzite.

The Precambrian basement is exposed for a long distance in the horsts marking the limits of the two sides of the Ṣa'dah graben. The east horst is pink granite near Ṣa'dah, and gneiss and mica schist farther north. North of Wādī Akwām the basement includes white marble much deformed by tectonic movements. The marble is locally mineralized by ilmenite at the contact with gabbro intrusives. Farther north of Wādī Akwām (tributary of Wādī Najrān), the white marble crops out as lenses appearing as small white hillocks surrounded by fluvial deposits.

Toward the Saudi Arabian frontier, the basement is composed of grayish-black mica schist and gneiss oriented north to south and includes some granitic massifs.

The west Ṣa'dah horst consists, from south to north, of mica schist, granite and pegmatite, biotite schist, and quartzite locally containing magnetite.

Compared lithologically with the Precambrian of Saudi Arabia, the basement would be the equivalent of the oldest formations grouped in the Hali Schist.

SEDIMENTARY ROCKS

WAJID SANDSTONE

A well-stratified sandy conglomeratic formation covers the Precambrian basement for a great distance east and north of the Jawf area and north of Ṣa'dah

(fig. 3). The southern boundary east of Al Jawf is a fault. Some remnant hills (Jabal an Nu'aym) still exist in small isolated grabens west of the Ṣa'dah depression.

This formation is composed mainly of well-rounded white quartz sandstone and conglomeratic gravel lenses. In Jabal Dalhān, north of Ṣa'dah, it exceeds 200 m in thickness. Apparently, the Wajid Sandstone represents deltaic deposition by rivers flowing from the southeast. Toward Wādī Najrān, the sandstone forms a thin cover over the plateau, a cover partly removed by the wadis and their tributaries. To the north, the Wajid Sandstone is less coarse grained, possibly formed, in part, of eolian deposits.

The stratigraphic contact between the Wajid Sandstone and the Kohlan Series was not observed because a fault separates the Wajid and Kohlan where they approach each other. Sedimentary conditions for these two sequences are quite different. The percentage of quartz is very high in the Wajid and greatly exceeds that of the Kohlan. Owing to the complete lack of index fossils in Yemen, we must look for the stratigraphic evidence in Saudi Arabia. Near the frontier the Wajid Sandstone is mapped as being of Permian age or older (Brown and Jackson, 1959).

KOHLAN SERIES

Below the Upper Jurassic Amran Series in Jaba Muṣawwar, Lamare and Carpentier (1932) found sedi

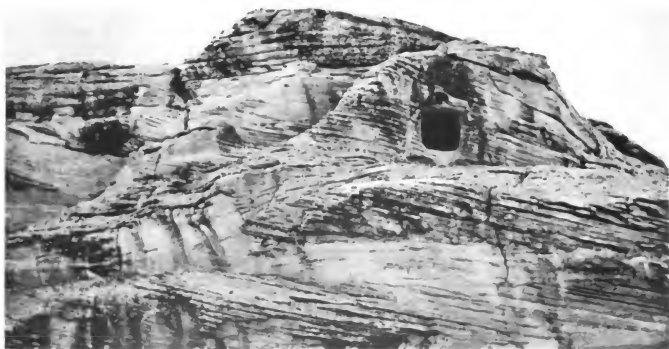


FIGURE 3.—Wajid Sandstone outcrop north of Ṣa'dah.

mentary rocks which they were able to date as Liassic from plant fossils found in the upper part. The beds were grouped by this author in the Kohlan Series, which is exposed mainly in the central and northern parts of Yemen. To the north the Kohlan Series does not go beyond the latitude of Sa'dah, and to the northeast it is bounded by the major horst which extends from Sa'dah-Jabal Baraṭ to Jabal al Lawdh. The southern extension includes a pre-Trap Series horst which bounds the At Tawilah-San'a Jurassic basin on the south (upper course of Wādī Surdūd). The series shows great facies variation from south to north and from east to west.

The series is highly arenaceous southward in the upper channels of Wādī Khawbah and Wādī al 'Urr, west of Jabal Shu'ayb, the highest mountain in Yemen. Resting on the basement and directly overlain by the Trap Series, the Kohlan in this area consists of yellowish-white sandstone with conglomerate lenses containing well-rounded quartz fragments. It is better exposed and thicker a little farther north in Wādī Nasīm (upper course of Wādī Surdūd). Here, the gneiss basement is overlain by about 150 m of white sandstone interbedded with many layers of conglomerate, violet fine-grained sandstone, and white crossbedded coarse-grained sandstone containing pseudonodules. There are also several zones of irregular accumulations of hematite. One hundred meters from the base, beds containing green-white, green, and red chert nodules are interbedded with conglomerate containing quartz fragments and green-gray shale debris. These are fluviolacustrine and neritic formations, and are probably equivalent to the green shale beds which crop out on the south side of Wādī Lā'ah where Lamare found a Jurassic flora. The neritic facies thins toward the north. The conglomerate beds, numerous north of Wādī al 'Urr, are almost completely absent in Wādī Surdūd, whereas shaly and tuffaceous beds are present to the north.

Section of Kohlan Series on south side of Wādī Lā'ah, north of At Tawilah
(see fig. 4)

	Thickness (meters)
Amran Series at top of section.	
Kohlan Series:	
Sandstone and shale; violet-red sandstone, and slaty shale overlain by gray shale	50
Shale, sandstone, and gray shale overlain by conglomeratic sandstone and 3 m of red shale	18
Shale, gray-green; includes large rounded blocks of granite, pegmatite, and gneissic mica schist as much as 1 m in diameter	7
Shale and conglomerate, a few meters of basal conglomerate containing basement fragments; some very thin conglomeratic layers with very fine well-stratified fragments, overlain by slightly green-gray shale	25
Total	100
Basement at base of section.	



FIGURE 4.—Wādī Lā'ah valley north of At Tawilah.

The upper calcareous gray shale contains the Amran Series fauna; thus the boundary between the Kohlan Series and the Amran Series is arbitrary because there was no break in sedimentation. From this section, it appears that the zone of large blocks about 7 meters thick separates an older complex about 25 m thick. Lamare without specifically stating so in his text, likewise depicted a conglomeratic bed with large fragments in his stratigraphic section.

The Kohlan Series may actually include two complexes of different age—the lower being more shaly. In any case, the sandstone facies thickens toward the west; in the lower course of Wādī Lā'ah, the Kohlan Series is several hundred meters thick (700 m according to O. Schuidt, oral commun., of C. Deilmann Bergbau). North of Jabal Muṣawwar, the series is about 300 m thick (Lamare, 1930b, and Wissmann and others, 1942). Thicknesses given by different authors do not compare closely because the upper boundary of the Kohlan Series is difficult to determine.

A complete section of the Kohlan Series is not exposed in any part of the Sa'dah area. Nevertheless, a part of this series about 125 m thick is exposed north of As Sinnārah (Jabal 'Abah), the mountain on which the

fortress of Sa'dah is constructed (fig. 5). From observations made west and southwest of Sa'dah, it seems probable that a complete Kohlan section is exposed at Jabal 'Ablah.

Section of Kohlan Series at Jabal 'Ablah, north of As Sinnadrah
Amran Series at top of section.

Kohlan Series:	Thickness (meters)
Sandstone, gray, hard, with worm tracks. Progressive transition to the overlying Amran Series.....	15
Sandstone, white, crossbedded.....	10
Sandstone, white, friable, crossbedded; red sand with ripple marks.....	26
Sandstone, calcareous and vuggy.....	14
Sandstone, gray, light-gray to yellow, friable.....	10
Sandstone, coarse-grained, red and yellow, crossbedded, and white poorly cemented sandstone.....	18
Shale, pebbly; conglomeratic layers with gray shaly cement and fragments as much as 10 cm in diameter.	20
Clay shale, light-gray.....	2
Sandstone, coarse-grained, with a red crossbedded band and irregularly disseminated pebbles and gravelly layers.....	8
Conglomerate, coarse; fragments as large as 10 cm in diameter; contains pebbles of volcanic rocks.....	2
Total.....	125

Basement at base of section.

These observations show that at the time of Kohlan deposition a zone of subsidence, which is now more

pronounced toward the Red Sea, existed in central Yemen.

AMRAN SERIES TYPE LOCALITY

The calcareous formations which crop out over a large part of Yemen, especially in the north, were grouped by Lamare in the Amran Series. 'Amrān, a town about 40 km from San'a, is in the bottom of a northeast-trending secondary graben. It has not been possible to locate precisely where Lamare established the type section, but he does show a figure in which he defines the Amran Series (Lamare, 1930b, p. 52).

The fossils of Jurassic age found in the lower part of the Tawilah Group, as defined by Lamare (beds 13 and 14), permit modification of the type section and the proposal of the outcrop in the south side of Wādī Lā'ah as type locality of the Amran Series. All the sedimentary sequences of Yemen except the Wajid Sandstone are exposed in this valley.

The Amran Series crops out mainly in the Sa'dah-Jabal Muṣawwar-Ma'rib area, although it formerly covered the entire country. In fact, traces of Amran rocks are found in the extreme eastern sector of the country, notably in the desert area of Sāfir, in the far south near the frontier along Wādī Banā, as well as in the west in an isolated horst which is uplifted through the Trap Series. The facies varies from place to place but is everywhere calcareous, a characteristic which



FIGURE 5.—Granitic basement and overlying Wajid Sandstone in fault contact with Jurassic sandstone and limestone. Walls of Sa'dah in the foreground.

easily distinguishes this series from the upper sandstones and from the lower shales and sandstones.

In the type area, Lamare (1930b) estimated the series to be 320 m thick; however, the thickness is highly variable from place to place in relation to local subsidence. Since the first exploration, the Amran Series has produced fossils which establish its age as a Malm equivalent.

PALEONTOLOGY

Fossils collected by Botes (1912) in the Bâjil area:

Cidaris cenomanensis Cotteau
Eozgyra africana Lamarck
Ostrea syphax Coquand
Ostrea oureensis Choffat
Ostrea dieneri Blanckenhorn
Nerinea sp.
Natica sp.
Terebratula sp.
Rhynchonella sp.

Fossils collected by Lamare (1930b) in the 'Amrân-Kuhlân area:

Cidaris glandarius Lang
Rhynchonella moravica Uhlig
Terebratula subella Leymerio
Aricula cf. *A. gesneri* Thurmann and Etallon
Ostrea suborbicularis Roemer
Ostrea thurmanni Etallon
Alectryonia pulligera Goldfuss
Eozgyra bruntrutana Thurmann
Modiola subangustissima Dacqué
Mytilus subpectinatus d'Orbigny
Arca subulata d'Orbigny
Isocardia (= *Cromyia*) *striata* d'Orbigny
Lucina subulata Roemer
Cardium banneanum Etallon
Pholadomya protei (Brongniart)
Anatina (= *Cercomya*) *striata* d'Orbigny
Anatina (= *Cercomya*) sp. indet.
Natica hemisphaerica Roemer
Natica sp.
Tylostoma sp. indet.
Perisphinctes cf. *P. virguloides* Waagen
Perisphinctes aff. *P. praetenuocylus* Waagen
Perisphinctes (*Virgatites*) cf. *P. dorsoplanus* (Vishchinskoff Burckhardt)

Fossils collected by Herbert Karrenberg (in Basse and others' 1954) north of San'a:

Modiolus (*Pharomylus*) cf. *M. perplicatus* Etallon
Eozgyra nana (J. Sowerby)
Eozgyra sp. indet.
Lophia karrenbergi Basse
Gryphaea balli (Stefanini)
Pracconia rhomboidalis (Phillips)
Protocardia somaliensis Cox
Cardium sp.
Pholadomya (*Homomya*) *inornata* J. de C. Sowerby
Nerinea retrogressa Etallon
Nerinea acron d'Orbigny
Nerinea binodosa Etallon
Cryptoplocus subpyramidalis Munster
Cryptoplocus n. sp. Basse
Cryptoplocus yemenensis Basse

Globularia hemisphaerica Roemer
Spinigera sp. indet.
Pseudocidaris thurmanni Etallon
Terebratula subella Leymerio
Comophylla thamnastroides Gregory
Pteriophyllum harenis Basse

Fossils collected by Genkens are listed in table 1.

LITHOLOGY

The Amran Series may be differentiated by facies in four areas, as follows: (1) South of Bâjil-San'a; (2) Wâdi Surdûd and Wâdi La'ah basins; (3) 'Amrân-Sa'dah-Al Jawf, and (4) Ma'rib-Sâfir.

SOUTH OF BÂJIL-SAN'A

South of the Bâjil-San'a area the Amran Series is exposed in small horsts uplifted through the Trap Series. In the northern part of this area, the series begins with a 1- to 2-m thick basal conglomerate that contains basement fragments 2 to 3 cm in diameter. Above this are beds of blue-gray limestone with lumachelles. This unit is overlain by the dark-gray limestone which is predominant throughout the whole series. The thickness of the series does not exceed 250 m.

In the southern part of this area, the top of the Amran Series is marked by 2 to 3 m of dark-gray shale and calcareous shale characterized in the upper part by signs of emergence and slightly violet shale and limestone.

Toward the west, the Amran Series limestones are dark blue and contain Mytilidae and *Ostrea* which were transported a great distance. Near the longitude of Ta'izz, the base of the series rests on the Precambrian and is composed of a few meters of pink quartzite and conglomerate containing small fragments overlain by thick beds of dark-blue limestone. A shaly complex about 200 m thick overlies the blue-gray limestone extending westward toward At Tihâmâh. This complex of green and violet shale with gypsum lenses is overlain by 100 m of dark shale, including beds of gray limestone, in turn overlain by calcareous sandstone (30 m thick) and a shaly complex with several thin lenses of marl and limestone. The contact with the Tawilah Group is very distinct.

To the south, the Amran Series consists of thick beds of dark-blue limestone, thinning to the east, which were deposited on the basement as a result of a marine transgression from the west. Many lumachelle beds show that the subsidence was slight and that the basin was progressively filled. After a period of emergence, a lacustrine period followed which was succeeded, in turn, by slight subsidence during which Upper Jurassic limy-marly and shaly deposits were laid down.

TABLE 1.—Fossils collected by F. Geukens

	NE of Amara	Kharbat 'Ali	Jabal Hamid	Al Uarf	Wadi Wakhid	Kharbat	Al Qub'a	As Khudrah	Jabal 'Abdo	Hab al Ahar	N of Al Tawilah	E of Maqhad	Al Hayaf	Ag Darg	SW of Qadab	Makrib (Jabal Hama)	Wadi Surhab	Khamir
<i>Bourquetia striata</i> J. Sowerby...								X										
<i>Burmihynchia?</i>										X								
<i>Camptonectes</i> aff. <i>C. virdunensis</i> (Buvignier)																		
<i>Ceratomya</i> cf. <i>C. plicata</i> Agassiz							X											
<i>Ceratomya</i> cf. <i>C. vimineus</i> (Gillieron)																		
<i>Ceratomyopsis</i> cf. <i>C. kiliani</i> (Roller)									X									
<i>Chlamys</i> (<i>Chlamys</i>) <i>curvicauda</i> Dietrich								X										
<i>Chlamys</i> sp.		X																
<i>Duganirhynchia?</i>										X								
<i>Eligmus</i> cf. <i>E. ovalis</i> (Stefanini)								X										
<i>Ezogyrus</i>																		
<i>Eligmus</i> cf. <i>E. rollandi</i> Douville									X									
<i>Ezogyrus nana</i> (J. Sowerby)	X	X																
<i>Ezogyrus Fourtau</i> Stefanini									X									
<i>Hemicidaris</i> (<i>Hypodidema</i>) <i>Macfadgani</i> (Currie)																		X
<i>Globularia</i> sp.		X																X
<i>Homomya inornata</i> (J. de C. Sowerby)																		
<i>Inoperna perpicata</i> (Etallon)																		
<i>Luna</i> (<i>Plagiostoma</i>) sp.		X																
<i>Luna</i> (<i>Plagiostoma</i>) <i>harrisi</i> Darque											X							
<i>Lophia solitaria</i> (J. Sowerby)																		
<i>Macromya</i> sp.																		
<i>Macromya aequalis</i> Agassiz									X									
<i>Modiolus imbricatus</i> J. Sowerby																		
<i>Modiolus jurensis</i> (Roemer)							X											X
<i>Brachidontes</i> (<i>Arcomytilus</i>) <i>laimaitrensis</i> (de Loriol)																		
<i>Nerinea</i>	X								X									
<i>Ontra</i>					X									X			X	
<i>Pholadomya</i>			X															
<i>Pholadomya aubryi</i> Douville														X				
<i>Pinna</i> cf. <i>P. stoliczkae</i> Cox																		
<i>Pseudocidaris thurmanni</i> Etallon		X																
<i>Somalirhynchia</i> sp.																	X	
<i>Somalirhynchia africana</i> Weir																		
<i>Somalirhynchia africana</i> var. <i>mesoloba</i> Muir-Wood																		
<i>Terebratula</i> cf. <i>T. bicanaliculata</i> Schlothem											X							
<i>Terebratula ovalis</i> Stefanini											X							
<i>Terebratula</i> sp.			X	X		X												X
<i>Terebratula supajurensis</i> (Thurmann)														X				
<i>Trochalia</i> cf. <i>T. yemenensis</i> (Bass)			X															
<i>Trochalia depressa</i> (Volz)																		
corals						X			X									
echinoids						X					X							
gastropods														X				
pelecypods					X													
plant debris																		
stromatopores									X						X			

Wādī Surūd and Wādī Lā'ah Basins

In the Wādī Surūd-Wādī Lā'ah basins, the upper and lower boundaries of the Amran Series are more difficult to determine. This is natural considering that in this area subsidence began before deposition of the Amran Series and continued into later epochs. For example, on the north side of the Wādī Surūd valley near the junction with Wādī al Ahjar, the lower sandstone series (Kohlan Series) grades progressively upward into limy and marly beds of the Amran. In that area the series, at least 360 m thick, consists of about 300 m of pure limestone and shaly limestone. These calcareous rocks are overlain by light-green and light-yellow shale and some sandy beds that enclose alternating layers of black shale and marl. This sequence grades progressively upward into sandy conglomeratic beds of the Tawilah Group.

In the upper channel of Wādī al Ahjar, the shaly-marly part of the Amran becomes more continental, whereas the limestone becomes more marly.

Section of Amran Series in upper channel of Wādī al Ahjar
Conglomeratic sandstone of Tawilah Group at top of section.

Amran Series:	Thickness (meters)
Sandstone and violet shale.....	20
Sandstone, ribbed; includes plant remains and a few beds of nodular sandstone.....	20
Shale, violet and green.....	15
Total.....	55

Typical limestone and marl below.

In this upper part of the Amran Series, beds of gypsum and dark bituminous shale increase toward the east, as seen in the east side of Wādī al Ahjar, and have been recognized north of Ṣan'ā in wells drilled in 1953 by German engineers to study the bituminous shale.

In spite of the gradual transition to adjacent series, the most complete section and the easiest to study is in the south side of Wādī Lā'ah.

Section of Amran Series in south side of Wādī Lā'ah

Tawilah Group at top of section.

Amran Series:	Thickness (meters)
Limestone and shale: shaly limestone, interbedded gray shale, and a few limestone beds containing many large sea urchins are overlain by alternating marly limestone and light-yellow argillaceous shale, many spicules, and <i>Lima (Pagiostoma) harronisi</i> <i>Darqué</i>	140
Limestone, thick-bedded; large <i>Ostrea</i>	50
Limestone and shale: complex of thick beds of light- gray limestone separated by shale lenses; toward the top the limestone becomes more marly and yellow... 170	
Shale, calcareous, gray; <i>Terebratula</i> cf. <i>T. bicanaliculata</i> <i>Schlotheim</i> and <i>T. aualites</i> Stefanini.....	20
Total.....	380

Kohlan Series at base of section.

The Amran Series thus consists of 380 m of predominantly light-gray limestone, the upper part of which contains a shaly-marly-limy complex 90 m thick. This thick sequence occurs, however, in the axis of subsidence; toward the north and west the Amran Series is not as thick.

Just south of Ath Thillah, the top of the calcareous Jurassic rock is in direct contact with crossbedded gravelly and sandy beds; at the contact is a conglomeratic breccia having calcareous cement. This is the margin of the Jurassic basin which emerged prior to the Cretaceous.

Toward the west in the direction of Maḥwad, the upper part of the light-gray limestone containing *Trochalia yemenensis* is overlain by about 20 m of sandstone interbedded with generally violet shale and limestone overlain by red sandstone. The sharp thinning of the marly-limy beds seen at At Tawilah, the arenaceous facies, and the violet coloring show that the Maḥwad area represents the western margin of the Late Jurassic basin.

The Jurassic reappears farther to the east on the west flank of a large anticline with a Precambrian core, where a sharp thinning of the Amran Series is also observed. The upper marly-limy part seems to be completely eroded here, and the base of the sandstone of the Tawilah is composed of conglomerate with limestone fragments.

'AMRĀN-SA'DAH-AL JAWF

In the 'Amrān-Sa'dah-Al Jawf area only rocks of the Amran Series crop out. Bounded on the northeast by faults and on the west by unexplored ravines, the area is not favorable for paleogeographical study. The region is characterized by predominantly light-yellow marly limestone, reminiscent of the upper part of the Amran Series in the Wādī Lā'ah valley. That these are shallow-water deposits is indicated by (1) many intercalated sandy layers and interstratified gypsum lenses, as for example, at Al Ḥarf southwest of Sa'dah, (2) claystone lenses and crossbedded sands with plant debris alternating with calcareous beds containing globular stromatoporoids and isolated corals, (3) beds filled with *Cidaridae* spicules, (4) beds showing traces of emergence and crossbedded sandy limestone.

The stratigraphy of the top and bottom of the series is more complex. Toward the base the Amran Series passes without interruption into the Kohlan, as demonstrated in the section near Jabal 'Abloh southeast of Sa'dah.

The upper part is exposed in the syndinal axis in the 'Amāsiyah area and consists of a dark-yellow to buff sandy layer containing plant debris.

MA'RIB-SÄFIR

The Amran Series is exposed in the desert region of Ma'rib-Säfir, but rare outcrops only give a general idea of the evolution of this part of Yemen.

The base of the series rests on the metamorphic basement exposed on the southwest side of Jabal Balag, west of Ma'rib. The basal part consists of 1 to 2 m of coarse-grained quartzite overlain by oolitic limestone and calcareous and sandy shale. The series itself is composed of light-yellow marly limestone similar to that at Sa'dah, but containing, on the east side of the jabal, many beds of alabaster and white marble which were quarried in ancient time. Eastward near Säfir, the Amran Series consists of major salt deposits overlain by bituminous shales, several meters of gypsum, and yellow-gray argillaceous and calcareous shale containing fish remains (fig. 6). The character of the rocks in the upper part of the Amran Series indicates a major isolated basin characterized by desiccating conditions.

TAWILAH GROUP

The Tawilah Group is composed mainly of white coarse-grained sandstone containing at irregular intervals conglomeratic layers of rounded or subangular quartz fragments; red sandstone is intercalated locally.

In the upper part, generally immediately below the Trap Series, are beds containing globules or nodules of hematite. To date, no fossils have been collected from this group, which is considered to be of Cretaceous age by reason of geometric relationships.

Type section of the Tawilah Group at Jabal al Tawilah
(see fig. 7)

Medj-zir Series at top of section.

Tawilah Group:	Thickness (meters)
Sandstone, white, crossbedded; coarse conglomerate lenses.....	120
Sandstone and shale; violet shale in thin beds interstratified in white sandstone.....	20
Sandstone and shale; white sandstone with conglomerate layers alternating with red and green shale.....	40
Total.....	180

Amran Series at base of section.

The delineation of the upper boundary is rather arbitrary in the zones of subsidence, such as in the zone west-northwest of Šan'a, although breaks in sedimentation occur elsewhere which allow more precise determinations of the boundaries of the group.

Because coarse-grained sandstones and gravelly layers everywhere characterize the Tawilah Group, the shaly-sandy transition beds (55 in thick) containing

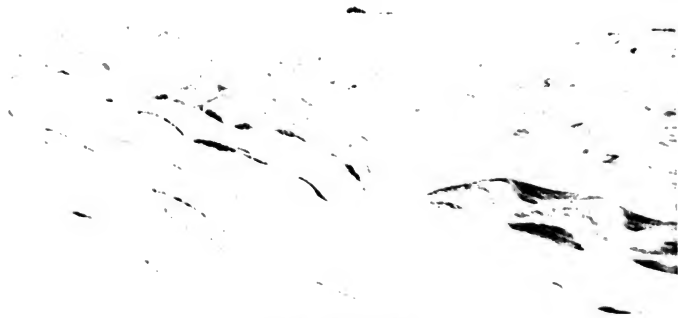


FIGURE 6.—Salt dome at Säfir.



FIGURE 7.—Tawilah Group exposures at the town of At Tawilah.

plants were considered Jurassic. These beds crop out in the upper channel of Wādī al Ahjar above Jurassic limestone.

The group is less thick (150 to 200 m) in the area north of Ta'izz where it may be studied in isolated horsts. At the base is a gray brecciated bed, about 1 meter thick, containing limestone fragments and is overlain by numerous conglomerate beds interstratified in coarse-grained sandstone.

The upper part includes white sandstone with layers of irregular hematite nodules, crossbedded sandstone, conglomerate, and finally a few lava flows. This alternation, however, is only local and shows that volcanic activity began with local extrusions.

East of the Trap Series (Jabal Tiya'l), the Tawilah Group is no more than 150 m thick. There, the base is a conglomerate containing fragments from the Anran Series, which demonstrates active erosion at the time of the Cretaceous transgression.

Stratigraphic observations prove that post-Jurassic tectonic movements produced undulations with a large radius of curvature. The margins of the basin were elevated, eroded, and the sedimentary debris deposited conformably on the earlier beds in the center of the

basin. Toward the margins the contact is slightly unconformable, and the basal beds of the Tawilah Group contain pebbles of the underlying Jurassic limestone.

The Tawilah Group extends slightly beyond the Trap Series to the north and east. The extent of the Tawilah Group corresponds very closely to that of the Trap Series, as if the Trap Series has protected the Tawilah from erosion.

MEDJ-ZIR SERIES

LITHOLOGY

The morphology between At Tawilah Kawkabān San'a and Wādī as Sirr is dominated by steep cliffs that are partly due to tropical erosion, which tends to form a peneplain and inselberg topography. These cliffs contain numerous caves (ancient Himyaritic tombs?) and consist of whitish-gray coarse-grained sandstone and conglomerate layers containing quartz fragments and ferruginous layers.

In the Al Gharās area, just north of Majzir, the cliffs expose Tertiary formations lithologically very similar to the underlying Cretaceous rocks.

Section of the Medj-zir Series in cliffs just north of Majzir (Al Gharda area)

[Total approximate thickness of Medj-zir Series, 120 m]

Trap Series at top of section.

Medj-zir Series:

Sandstone with ferruginous, spherulitic concretions and nodules; appears to be a paleosol that covered the area before the extrusive phase.

Sandstone, white, mottled red, becomes finer grained and more shaly.

Sandstone, white.

Clay, light-gray, slightly hardened.

Sandstone, white.

Shale, green-red, a few meters thick.

Sandstone, white, fine, slightly calcareous (altered), fossiliferous; contains a 30-cm bed filled with worm tracks.

Sandstone, white, coarse-grained, quartzitic, very compact; contains crossbedded layers altered to a darker color (these are displayed over a great distance).

Conglomerate, 10 to 30 cm thick, of rounded quartz fragments 1 to 3 cm in diameter.

Tawilah Group sandstone at base of section.

The lowermost conglomerate layer is considered to be the base of the Medj-zir Series, and lies with apparent conformity on sandstone beds with very similar facies more than 200 m thick. At Majzir the thickness of Tertiary rocks is about 120 m. These form the upper part of the sandstone cliffs on two sides of the Rawdah plain, north of San'a; they are also seen on the summit of Kawkabān-At Tawilah (fig. 8) where the fossiliferous

layers are found in the fortress constructed on the south side of the cliff which dominates the town of At Tawilah.

This series is no longer present east of the Trap Series and was not recognized in sections between At Tawilah and Maḥwad, nor in strata exposed in horsts uplifted through the Trap Series.

The sedimentary sandy series which crops out in horizontal attitude east of the Trap Series dips under the Jabal Ash Sharafah (Tiyāl) massif, but the Medj-zir is not present there. On the other hand, it is apparent that the massif Ḥadūr ash Shaykh, in the Ath Thillah area, is a dome and that the sedimentary series dip toward the south.

Although the age of these tectonic deformations cannot be precisely determined, the Medj-zir Series appears to be deposited in a fairly well defined basin. It is difficult to establish the direction of the transgression, but the series is apparently thicker to the west and, therefore, the sea probably came from this direction. In fact, at At Tawilah, where the Medj-zir Series is no longer protected by the Trap Series, it is the same thickness as at Majzir town and the rocks are finer grained and more calcareous (the calcium carbonate being in large part removed by solution).

FOSSILS AND AGE

The At Tawilah area has furnished only internal molds of *Nerinea*, as much as 7 cm long, whereas



FIGURE 8.—Medj-zir Series above Tawilah Group in the cliffs at Kawkabān.

at the town of Majzir, northeast of San'a, the fauna includes the following, which date the Medj-zir Series as Paleocene:

Myliobatus sp.
Campanile, internal molds
Calyptacea sp.
Architectonica sp.
 brachiopods

The sequence at Majzir also includes slabs of irregular elliptical outline (from 3 to 20 cm long) filled with small triangular forms grouped into hexagons that are probably due to recrystallization of calcite.

IGNEOUS ROCKS

TRAP SERIES VOLCANIC ROCKS

The southwest part of Yemen, almost one-quarter of the country, is covered by volcanic rocks grouped into the Trap Series. The Trap Series is made up mainly of alternating lava flows, basalts, andesite, or trachyte porphyries, and different types of varicolored tuffs (fig. 9). The maximum thickness is difficult to estimate because of faults but is locally in excess of 1,200 m.

Throughout the Trap Series are seen intrusive basaltic rocks irregularly distributed as dikes, sills, or laccoliths. The old major volcanic centers are rather rare. They are noted either by lava flows which thicken toward the centers or by the transition from tuffs to conglomerates.

Volcanic centers are also marked by chimneys standing above the general ground level. Large dikes, some of which can be followed for several kilometers, are seen in numerous places.

INTER-TRAP DEPOSITS

During the period in which the Trap Series formed there were quiet intervals, some of long duration. During these quiescent periods four types of inter-Trap deposits accumulated:

1. Fresh-water deposits, probably lacustrine, which are fossiliferous: generally contain bituminous beds and plant and fish remains.
2. Typical alluvial deposits with fragments of partially carbonized wood.
3. Sandy deposits without fossils (fluvioeolian?).
4. Paleosol, generally lateritic, at some places developed along plane surfaces, and locally cutting different beds.

The fossiliferous beds include small gastropods, lamellibranchs, and ostracods. These are *Sphaerium* sp., *Amerianna* sp., *Melanoides* (*Tarebia*) cf. *M. acuta* (Sowerby). These fresh-water fossils, which suggest an Oligocene to Miocene age, occur from north of San'a to south of Ta'izz. Mr. R. W. Morris, of the Arabian American Oil Co., recognized nonmarine ostracodes: *Candona* sp., *Cyprideis* sp., *Gomphocythere* sp., and *Cypridopsis*(?) sp.



FIGURE 9.—Trap Series near Zarajah.

AGE

Volcanism probably started in the south toward the end of the Cretaceous but became more intense and extensive during the Tertiary. It is characterized by extrusive and explosive periods related to tectonic deformation along faults. Volcanic activity continued into the Recent.

LACCOLITHS

GEOGRAPHIC DISTRIBUTION

The area between 'Amrān and Sa'dah, north of the extension of the Trap Series, has major laccolith massifs of granitic composition, some deeply breached by erosion (fig. 10). Such examples occur at Jabal Ramid south of Hūth and in the hills near Jabal Maḥḥūq in the Jawf area (fig. 11). The granitic laccoliths are especially noticeable in the calcareous Amran Series.

In Jabal Ramid, the granite exposed in the center grades to a microgranite near the contact with limestone beds; the sedimentary rocks are not influenced by contact metamorphism except over a very thin interval.

AGE

Supposedly, the emplacement of the laccoliths is of the same age as the Trap Series, hence mainly Tertiary.

RECENT GRANITES

Gray-white granite hills protrude locally above the general topography carved in the Trap Series. These intrusive massifs deform the Trap Series on their flanks, and thus they are dated as post-Trap. Some intrusions reach 10 km in length and a few kilometers in width, but others may be less extensive and appear as lenticular dikes from 0.1 to 1.5 m wide.

Silicic granitic intrusions (leucocrats, holocrystallines) enclose crystals of tourmaline (Jabal Hufāsh) or amphibole (Jabal Ṣabir, fig. 12).

RECENT VOLCANOES

Recent (Holocene) volcanoes are those which have retained their typical shape (crater or cone) and whose direction of flow has been influenced by the existing topography.

Recent volcanoes are grouped in three volcanic fields: (1) Sa'u'ā-'Amrān, (2) Sirwāh-Ma'rīb, and (3) Dhamār-Radā'. Isolated volcanoes are present elsewhere throughout the country.

In the Sa'u'ā-'Amrān volcanic field it is possible to distinguish several extrusive phases by comparing the development of river terraces to the southwest of 'Amrān. North of Sa'u'ā there are also volcanoes of historic time.

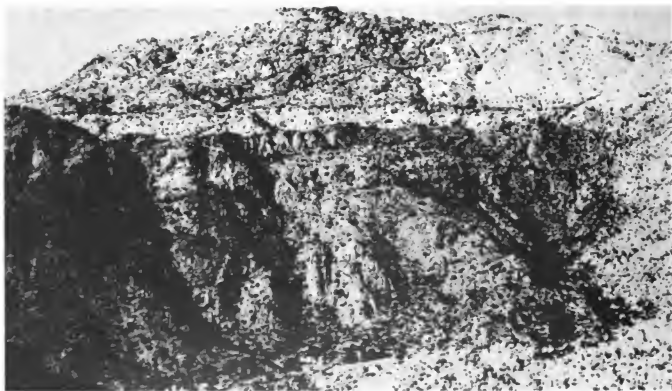


FIGURE 10.—Laccolith in the Kohlan Series in the upper course of Wādī Surdūd.

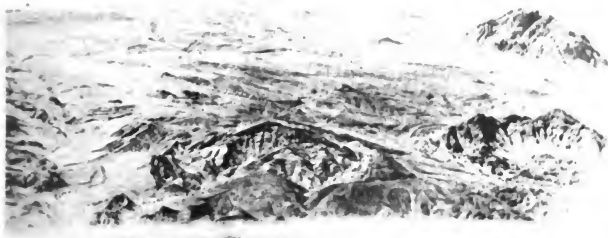


FIGURE 11.—Laccoliths in Al Jawf region.



FIGURE 12.—Recent granitic massif of Jabal Sabir and city of Ta'izz at base of volcanic cone.

Volcanoes in the Širwāb-Ma'rib field are of several types. South of the Širwāb-Ma'rib road are volcanoes having large cones of light-yellow tuffs surrounding the central peaks. These volcanoes have supplied thick stratified deposits of white-yellow tuff which extend for several kilometers in the direction of Wādī Adhanah. North of the road lie basaltic volcanoes with numerous adventitious craters, characterized by long flows which thin to the south.

About 3 hours walk east of Širwāb is a depression of an old crater; the tuff and agglomerate beds dip gently to the exterior and enclose blocks of gneiss and granite up to 50 cm in diameter, attesting to the violence of the explosive phase.

Volcanism in Dhamār-Radā' (fig. 13) is the most recent in Yemen and the field still contains solfataras (sulfurous vents). The volcanic field is related to an east-west-trending fracture zone, along which are the main centers. Small volcanoes rise from the floor of the depression, especially in the eastern part. Seismic shocks are very numerous in this area.

STRUCTURE

The surface features in Yemen fit into two large very distinct categories: (1) the folded metamorphic basement of Precambrian age in unconformable contact with (2) the unmetamorphosed subhorizontal sedi-

mentary rocks. Exposures of the lower beds of the sedimentary rocks as well as the basement depend largely on erosive activity.

Orogenic movements, generally with a great radius of curvature, have locally influenced the structure of the country. For example, the area between Ash Sharafah and Ma'rib is a large dome plunging to the north.

Synclines occur particularly in the north—north of Wādī Mawr and in the 'Amāsiyah area, south of Sa'dah. The area covered by the Trap Series corresponds in reality to a deep depression. The shape of the depression is most pronounced at the eastern border of the Trap Series, especially in the vicinity of Jabal Tiḡāl.

Other undulations are less striking, as for example, the east-west-trending anticline at Jabal Ḥaḍūr ash Shaykh and Jabal Muṣawwar. The Ṣan'ā area is a large syncline which extends from Wādī al Ḥajar in the west to Jabal Tiḡāl in the east and is the site of the old Jurassic basin.

From the fact that the coastal, or At Tihāmah, part of Yemen is a graben and the eastern part a horst, it is deduced that the general structure must be dominated by subvertical faults oriented preponderantly from the north-northwest to the south-southeast, subparallel to



FIGURE 13.—Recent volcanoes near Radā'.

the Red Sea graben and at right angles to the Gulf of Aden, which trends east-northeast-west-southwest.

Innumerable faults, in fact, cut through the country, many bounding secondary grabens and horsts. The whole zone of contact between the Red Sea plain and the mountainous region is marked by faults trending north-northwest-south-southeast. One graben parallel to the Red Sea forms the main Al Jawf depression in the northeast, which is joined by a graben that follows the alignment of the Gulf of Aden, and forms the Ramlat as Sab'atayn desert. Tectonic alignments are also oblique to the former directions; this is true of the 'Amrān graben and the secondary graben between Harb and Ma'rib. Many secondary grabens in the area covered by the Trap Series are sometimes difficult to distinguish from the fluvial flat-bottomed valleys covered by thick alluvium (plains of Sa'nā, Ma'bar, Yarīm, Al Janadīyah, and others). However, grabens are readily distinguished in places where recent volcanoes along the bordering faults have spread lavas toward the depressed part (Dhamār, Radā', and 'Amrān grabens) (fig. 14). These grabens are characterized by a system of faults which form steps along the margins and small horsts which rise in the graben floors. In many places the steps look like large landslides on the sides of the horst.

Besides the system of parallel faults, there is in places a system of perpendicular faults outlining blocks which could be large horsts (north of Ta'izz) and small isolated massifs (Jabal Kanin). The faults are easily located in the sedimentary series where they bring heterogeneous rocks into contact (fig. 15) and thus

permit an evaluation of the throw of the fault. By contrast the faults are more difficult to study in the Trap Series.

Tectonic deformation along faults is not limited to epirogenic movement related to the formation of the Red Sea. The fact that south of Wādī Surdūd the Trap Series rests directly on the Kohlan Series and that the Amran Series and Tawilah Group disappear suddenly along the faults (fig. 16) proves that the generally east-west oriented faults locally deformed the country long before the deposition of the Trap Series. Faults are so numerous locally that they cannot be adequately depicted on a map. The most tectonically active valley was the Wādī Surdūd, especially its upper and middle courses. Although the dip of the faults is generally steep, some have the appearance of overthrusts (for example, between Maḥwad and Aṭ Tawilah where the Amran Series is thrust over the deformed Tawilah Group for a long distance).

Magma has often penetrated along faults, and the basalt has simply filled up the open fissures. Secondary cracks cut the basalt dikes, as is evinced near Ḥayḍān, west of Ta'izz, where the center of a basalt dike cutting Cretaceous sandstone contains a vertical bed 50 cm thick composed of detrital fragments. In other places basaltic intrusions along faults have torn off large fragments of the confining rocks, as for example along the faults which outline the horsts north of Ta'izz.

Tectonic deformation possibly occurred after the emplacement of the dikes. In fact, west of Aṣ Saḥīyah (north of Ta'izz), basalt fragments are intermingled with blocks of Cretaceous sandstone (2 to 3 m wide)

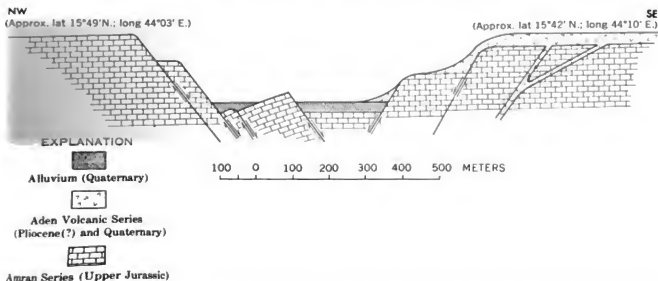


FIGURE 14.—Profile of 'Amrān graben. Surface of alluvium is at elevation of 2,100 m; surface of the Amran Series to the northwest is at 2,450 m.

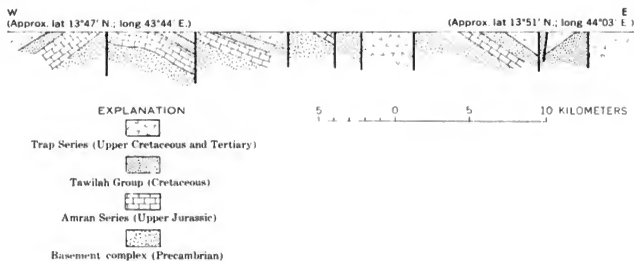


FIGURE 15.—Schematic profile of north of Ta'izz showing horst through Trap Series.

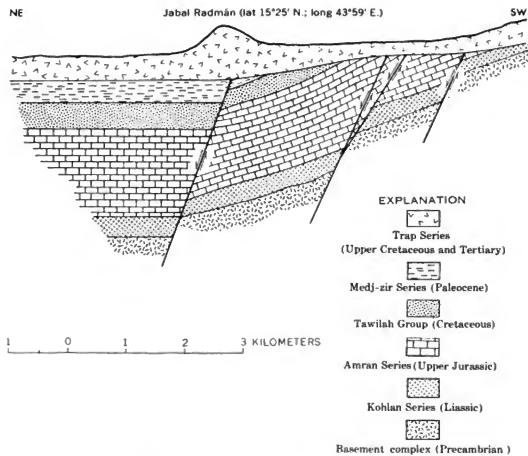


FIGURE 16.—Structure section in vicinity of Jabal Radmān.

along major faults forming a thick breccia zone. Many of the breccias along the faults are restricted and disappear in a short distance as along the Kawkabān fault. The fault traces are indicated by abrupt changes in dip; some subhorizontal beds become vertical near a fault contact (fig. 17). Faults that can be followed for a great distance are generally cut by small right-angle faults of much less throw and later origin than the main fault.

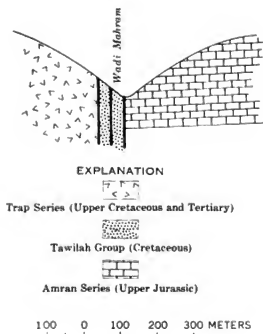


FIGURE 17.—Profile of Wādī Maḥrum (lat 15°20' N.; long 43°55' E.) showing fault contacts of Trap Series, Tawilah Group, and Amran Series.

Southwest of Maḥwad, not far from the recent granites of Jabal Hufish, sandstones of the Tawilah Group are bounded on two sides by faults. This is the only locality known to date where the sandstones are partially changed to quartzite by dynamic or contact metamorphism.

Thermal springs related to faults (especially along the Red Sea) explain the existence of many small communities called Ḥammām 'Alī. Hot springs are most frequently found in the Trap-covered areas, although some hot vapors are emitted from caves in the limestone plateau north of Ḥāth (near Al Ḥarf).

Mineralization along faults is very rare and is present only in the north of the country where faults affect the basement and the Jurassic limestone. Hematite deposits occur just east of Sa'dah and about 30 km northwest of Sa'dah near Majd. Ilmenite deposits

are found in the Wādī Akwān basin northeast of Sa'dah.

Toward the end of the Mesozoic, extrusion of basalt began in conjunction with the formation of the Red Sea. However, it was only from the Oligocene on that the graben took the form of a depressed area without outlet.

Major lava flows in association with fracturing, very active during the Oligocene and Miocene, extended over the southwestern part. In the same epochs the unstable zone of the Red Sea subsided in a series of secondary grabens, now filled mainly by salt and terrigenous deposits carried by rivers which adjusted to the new topography. At nearly the same epochs laccoliths were injected in the northern part of the country.

Deformation along faults during the Pliocene and Pleistocene played the most important role in the morphology. Warping caused the formation of an outlet of the Red Sea to the ocean and accentuated the horst scarp by favoring the development of rivers and increasing headward erosion.

During the calmer and drier period of the Holocene (Recent), corals developed in the Red Sea and rivers continued to fill the east part of At Tihāmah while eolian deposition predominated toward the coast.

GAZETTEER

Published sources listing Yemen place names in the original Arabic are few and incomplete. The forms used in this work were transliterated in the system of the Board on Geographic Names by James P. Mandaville, Jr., Arabian Affairs Division, Arabian American Oil Co. Spellings are based on written sources except those which could not be confirmed and are followed by a question mark.

The coordinates listed below refer to the middle courses of wadis, the highest points of mountain massifs, and the approximate centers of regional features.

Name	Lat N	Long E
Jabal 'Abīah(?)	16°56'	43°48'
Wādī Adhanah	15°12'	45°07'
Wādī al Aḥjar	15°28'	43°52'
Wādī Akwān(?)	17°02'	43°48'
'Amāsiyah	16°30'	43°50'
'Amrān	15°40'	43°56'
Bājil	14°58'	43°15'
Jabal Baluq	15°30'	45°19'
Wādī Banā	14°05'	44°32'
Jabal Barāt	16°47'	43°52'
Al Bayḍ	15°13'	44°36'
Jabal Dakhān(?)	15°34'	45°00'
Jabal Dullān(?)	17°07'	43°42'
Jabal Dūwān	14°45'	44°11'
Ad Dūyq	15°14'	44°45'

Name	Lat N.	Long E.
Dhamār.....	14°31'	44°28'
Al Gharar.....	15°35'	44°24'
Ujajah.....	15°40'	43°34'
Hamman 'Ali.....	14°42'	44°08'
Al Uarf.....	16°24'	44°11'
Uarif.....	14°57'	45°30'
Uaydan.....	13°41'	43°45'
Jabal Haylan.....	15°35'	45°12'
Al Qudaydah.....	14°46'	42°57'
Jabal Ufufah.....	15°13'	43°28'
Ufufah.....	16°18'	43°55'
Ibb.....	13°58'	44°11'
Al Janadiyah.....	13°40'	44°10'
Al Jawf.....	16°07'	44°30'
Wadi al Jawf.....	15°05'	44°30'
Jabal Kanin.....	15°32'	43°55'
Kawkabān.....	16°04'	43°58'
Khamir.....	15°19'	43°54'
Wadi Khawbah(?).....	15°59'	44°01'
Khawbat 'Ali.....	16°41'	43°57'
Khusran(?).....	15°42'	43°42'
Kuhlan.....	15°32'	43°34'
Wadi Lā'ah.....	16°07'	45°07'
Jabal al Lawdh.....	14°51'	44°15'
Ma'bar.....	16°38'	44°11'
Jabal Maftūq(?).....	15°20'	43°55'
Wadi Mahram(?).....	15°29'	43°32'
Ma'wad(?).....	17°06'	43°33'
Majd(?).....	15°34'	44°36'
Majir(?).....	15°29'	45°28'
Ma'rib.....	15°48'	43°18'
Wadi Mawr.....	13°46'	43°44'
Mujabib(?).....	13°19'	43°14'
Al Mukha.....	15°26'	43°38'
Jabal Musawwar.....	17°29'	44°08'
Wadi Najran.....	15°23'	43°56'
Wadi Nasim(?).....	16°55'	43°30'
Jabal an Nu'aym(?).....	14°30'	44°56'
Rada'.....	15°25'	43°59'
Jabal Radmān.....	15°48'	45°10'
Wadi Raghwān(?).....	16°16'	44°07'
Jabal Ramid(?).....	15°30'	45°50'
Ramlat as Sab'atayn.....	15°27'	44°13'
Rawdah.....	13°31'	44°03'
Jabal Sabir.....	16°58'	43°45'
Sa'dah.....	15°41'	46°09'
Safir.....	13°52'	44°03'
Aṣ Sa'fiah.....	16°45'	43°51'
Aṣ Sa'fā'.....	14°09'	44°35'
Safwan.....	15°23'	44°12'
San'a'.....	15°29'	44°42'
Jabal ash Sharafah.....	15°36'	43°50'
Uadūr ash Shaykh.....	15°19'	43°57'
Jabal Shu'ayb.....	16°55'	43°48'
As Sinnarah.....	15°33'	44°23'
Wadi as Sirr.....	15°27'	45°12'
Sirwāb.....	15°21'	43°41'
Wadi Surdūd.....	13°34'	44°02'
Ta'izz.....	15°30'	43°42'
Al Ta'wīsh.....	15°29'	44°42'
At Thāmah.....	15°37'	43°54'
Jabal Tiyyāh.....		
At Thillah.....		

Name	Lat N.	Long E.
Wadi al 'Urr.....	15°17'	43°55'
Wadi Wakhid(?).....	16°34'	44°03'
Wadi Wa'lan.....	15°05'	44°19'
Yarim.....	14°17'	44°26'
Zabid.....	14°10'	43°18'
Zarajah.....	14°54'	44°19'

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GEOLOGY OF THE ARABIAN PENINSULA

Aden Protectorate

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Geology of the Arabian Peninsula

Aden Protectorate

By J. E. G. W. GREENWOOD and D. BLEACKLEY

GEOLOGICAL SURVEY PROFESSIONAL PAPER 560-C

A survey of the geology of the Western Aden Confederation as shown on USGS Miscellaneous Geologic Investigations Map I-270 A, "Geologic Map of the Arabian Peninsula," 1963



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FOREWORD

This volume, "*The Geology of the Arabian Peninsula*," is a logical consequence of the geographic and geologic mapping project of the Arabian Peninsula, a cooperative venture between the Kingdom of Saudi Arabia and the Government of the United States. The Arabian-American Oil Co. and the U.S. Geological Survey did the fieldwork within the Kingdom of Saudi Arabia, and, with the approval of the governments of neighboring countries, a number of other oil companies contributed additional mapping to complete the coverage of the whole of the Arabian Peninsula. So far as we are aware, this is a unique experiment in geological cooperation among several governments, petroleum companies, and individuals.

The plan for a cooperative mapping project was originally conceived in July 1953 by the late William E. Wrather, then Director of the U.S. Geological Survey, the late James Terry Duce, then Vice President of Aramco, and the late E. L. deGolyer. George Wadsworth, then U.S. Ambassador to Saudi Arabia, and Sheikh Abdullah Sulaiman, then Minister of Finance of the Government of Saudi Arabia, lent their support to the plan. In November of the following year, 1954, Director Wrather approved the U.S. Geological Survey's participation and designated G. F. Brown responsible for the western Arabian shield region in which he had previously worked under U.S. foreign-aid programs. In January 1955 F. A. Davies, Chairman, Board of Directors, Arabian-American Oil Co., approved Aramco's participation and appointed the late R. A. Bramkamp, chief geologist, responsible for compilation of the area within the Kingdom where the sediments crop out. This responsibility fell to L. F. Ramirez following the death of R. A. Bramkamp in September 1958.

R. A. Bramkamp and G. F. Brown met in New York in February 1955 and planned the program, including scales of maps, areas of responsibility, types of terrain representation, and bilingual names. Thus there was established a cooperative agreement between the Kingdom of Saudi Arabia, the U.S. Department of State, and the Arabian-American Oil Co. to make available the basic areal geology as mapped by Aramco and the U.S. Geological Survey.

The agreement specified publication of a series of 21 maps on a scale of 1:500,000, each map covering an area 3° of longitude and 4° of latitude. Separate geologic and geographic versions were to be printed for each of the quadrangles; both versions were to be bilingual—in Arabic and English. A peninsular geologic map on a scale of 1:2,000,000 was to conclude the project.

High-altitude photography, on a scale of 1:60,000, of the Kingdom of Saudi Arabia was initiated during 1949 by the Aero Service Corp. and completed in 1959. Both third-order vertical and horizontal control and shoran were utilized in compiling the photography. This controlled photography resulted in highly accurate geographic maps at the publication scale which then served as a base for the geologic overlay. The topography of the sedimentary areas was depicted by hachuring and that of the shield region by shaded relief utilizing the airbrush technique.

The first geographic quadrangle was published in July 1956 and the last in September 1962. While preparation of the geographic sheets was in progress, a need arose for early publication of a 1:2,000,000-scale peninsular geographic map. Consequently, a preliminary edition was compiled and published in both English and Arabic in 1958. The second edition, containing additional photography and considerable new topographic and cultural data, was published in 1963. The first of the geologic map series was published in July 1956 and the final sheet in early 1964. The cooperative map project was completed in October 1963 with the publication of the 1:2,000,000-scale "Geologic Map of the Arabian Peninsula" (Miscellaneous Geologic Investigations Map I-270 A).

As work on the quadrangles progressed, geologists, companies, and governments working in areas adjacent to the Kingdom of Saudi Arabia were consulted by Aramco and invited to participate in the mapping project. The number of cooperating participants was expanded to 11, which included the operating oil companies in the peninsula and which are identified elsewhere in this text; the Overseas Geological Surveys, London; the Government of Jordan; F. Geukens, who had worked in Yemen; and Z. R. Beydoun, who had studied the Eastern Aden Protectorate. With the close cooperation of the authors, the new data were added to data already plotted on the base map of the Arabian Peninsula.

As the geological coverage of the peninsular map grew, the need for a text to accompany the map became apparent to both the U.S. Geological Survey and the Aramco geologists. Exploratory conversations were begun by Aramco with companies working in the other countries of the Arabian Peninsula for their participation in the preparation of a monograph on the geology of the Arabian Peninsula. Each author prepared a description of the geology of the area for which he was responsible, as shown in the sources of geologic compilation diagram on the peninsular map. The U.S. Geological Survey undertook the publishing of the volume as a professional paper, and the Government of Saudi Arabia was to finance its printing. It was early agreed that there would be no effort to confine the contributions to a standard format and that no attempt would be made to work out an overall correlation chart other than shown on the "Geologic Map of the Arabian Peninsula." Thus, the individual style of authors of several nationalities is preserved.

Cooperation and relations have been of the highest order in all phases of the work. The project would not have been possible without the full support of the U.S. Department of State, the Kingdom of Saudi Arabia, and all contributors. In fact, the funds which made publication of this volume possible were contributed by the Saudi Arabian Government.

The data provided by the maps and in the professional paper provide information for an orderly scientific and economic development of a subcontinent.



O. A. SAGER,
Arabian-American Oil Co. (Retired).



W. D. JOHNSTON, JR.,
*Former Chief, Foreign Geology Branch,
U.S. Geological Survey.*

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GEOLOGY OF THE ARABIAN PENINSULA

ADEN PROTECTORATE

By J. E. G. W. GREENWOOD and D. BLEACKLEY¹

ABSTRACT

This account of the geology of Western Aden Protectorate and of major basement rock groups of Eastern Aden Protectorate is based on photogeological interpretation and on data from a field survey during November 1961 to February 1962. Attention is concentrated mainly upon igneous and metamorphic rocks.

An assemblage of metamorphosed sedimentary and mafic igneous rocks, to which the term "Aden Metamorphic Group" is assigned, rests upon older gneiss and is invaded by syntectonic granite with associated zones of metasomatism and migmatization. Subsequent to the main period of regional metamorphism but prior to a later period of stress, plutonic intrusions of dioritic and gabbroic rock occurred; these were followed after a short interval by intrusions of granite. Older volcanic rocks of the Eastern Aden Protectorate are regarded as approximately contemporaneous with mafic intrusions of this phase. Slightly metamorphosed sedimentary rocks of Wadi Ghabar, Eastern Protectorate, are thought to represent uppermost basement rocks. Posttectonic granites of early Paleozoic age and mafic plutonic rocks of possibly similar age are described. Rare intrusions of alkaline granite are thought to be of Tertiary age.

An early phase of regional (dynamothermal) metamorphism is distinguished from a later phase of essentially dynamic type. The highest grade of metamorphism recorded is that of the almandine-amphibolite facies. The effect of syntectonic granite invasion upon metamorphic grade is considered.

A synopsis of the geology of basement rocks is given, and regional correlation of basement rocks made, in which the Aden Metamorphic Group is tentatively correlated with the main part of the Medina Series, and the Ghabar Group of the Eastern Protectorate with the Fatima Series of Saudi Arabia.

A section on the Aden Tmp Series includes petrographic examples and a discussion of relations with surrounding rocks and of the probable history of this phase of vulcanism. The age of the series is considered to be Late Cretaceous to Tertiary.

Dike rocks of three ages are present.

A relatively brief account of sedimentary rocks is largely based on the work of Heydoun in Eastern Aden Protectorate. Fossils collected from these rocks are listed.

An account is given of the Aden Volcanic Series, which consists mainly of basaltic lava flows of late Miocene, or Pliocene, to Recent age.

The structure of the Western Protectorate is considered in conjunction with that of the Eastern Protectorate. Basement

strike trends, hitherto not known in detail, are discussed and an account of folding and foliation is given. Since at least Jurassic times the region has suffered intermittent epirogenic uplift accompanied by faulting. A major phase of uplift of the main basement block of the Western Protectorate, associated with faulting principally along Red Sea trends, dates from late Cretaceous or early Tertiary times. A dominant feature in the Eastern Protectorate is the development of the Tertiary Ibadh-ranuf arch. Faulting of four main trends is described and a correspondence between these fault directions and those of the worldwide tectonic shear pattern is noted. Faulting in any one trend was not confined to a single period, and re-activation of ancient fault lines is suggested. A main phase of faulting of the Red Sea trend apparently occurred from Late Cretaceous until late Eocene times. A main phase of faulting of the Gulf of Aden trend dates from Miocene times. A general commentary on structure is given, in which it is suggested that the basement structural pattern results from the translation of a primary east-west stress by transeurrent movements along ancient shear lines.

In a section on economic geology the results of geochemical prospecting and of concentrate analysis are interpreted and discussed; occurrences of economic minerals are described. No deposits of any great commercial interest have been found.

A section on water resources completes the account.

A discussion of age determination results by Dr. N. J. Snelling appears as an appendix.

INTRODUCTION

PURPOSE AND SCOPE

The 1:2,000,000-scale geologic map of the Arabian Peninsula—prepared as an Arabian American Oil Company—United States Geological Survey project under the joint sponsorship of the Kingdom of Saudi Arabia, Ministry of Petroleum and Mineral Resources, and the U.S. Department of State—incorporates the Overseas Geological Surveys' 1:500,000 unpublished "Photogeological Map of the Aden Protectorate." The present report describes the geology of that part of the Arabian Peninsula which was mapped by the Overseas Geological Surveys (hereafter alternatively referred to as O.G.S.). The scope of the contribution, however, extends further than the explanation of geology shown on

¹ Of the Overseas Geological Surveys, London.

the map of the Arabian Peninsula. For example, the scale of the map precludes the portrayal of basement strike trends, which is a significant feature of the O.G.S. Photogeological Map. These structural lines are shown on illustrations accompanying this report. In brief, this account presents an outline of the more important findings of recent O.G.S. fieldwork in the Western Aden Protectorate, hereafter alternatively referred to as W.A.P.

Geological data from the O.G.S. Photogeological Map were necessarily presented for incorporation in the Arabian Peninsula geologic map before the results of the 1961-62 Aden field survey could be analyzed and collated. Thus, although amendments have been effected as much as possible in the Arabian Peninsula map, considerable amplification and changes are reflected in the present account. In particular, basement rock units have been further subdivided. Divisions shown in the geologic explanation of the Arabian Peninsula map and those of this account are equated in table 1, to which descriptive notes are added.

TABLE 1.—Rock units of Western Aden Protectorate and corresponding symbols on map of the Arabian Peninsula

Age	Unit name used in this report	Map symbol
Pliocene and Pleistocene to Recent	Eolian (dune sands)	Qe
	Superficial deposits, including alluvium, loess, silt, sand, gravel, and terrace and raised beach deposits	Qu
Late Miocene or Pliocene to Recent	Aden Volcanic Series	Qa
Early Eocene	Rus Formation	Tr
	Jesa Formation	Tj
Paleocene	Umm er Radhama Formation	Tu
Late Cretaceous to Tertiary	Alkaline granite	Included in PzpCg.
	Aden Trap Series	Tkt
Cretaceous	Tawilah Group	Kt
Jurassic	Unconformity	
	Amran Group and Khabian Formation	Ju
Early Paleozoic(?)	Major unconformity	
	Later mafic intrusions	Included in dr.
Early Paleozoic	Posttectonic calc-alkaline granite	Included in PzpCg
	Intertectonic calc-alkaline granite	
Precambrian	Intertectonic intermediate mafic plutonic intrusions	Included in dr.
	Syntectonic granite	Included mainly in gh and tr, also in part in PzpCg
	Aden Metamorphic Group	mr
	Older gneiss	Not shown.

The geological work by O.G.S. in Aden Protectorate has been primarily concerned with igneous and metamorphic rocks; during the recent field survey, work on sedimentary rocks, which are sparse in W.A.P., was mainly in connection with possible economic mineral deposits. The relatively brief account of sedimentary rocks contained in this report is based largely on the

divisions given by Beydoun (1960, 1961) in his descriptions of the sedimentary strata of Eastern Aden Protectorate, hereafter alternatively referred to as E.A.P.

The area covered by this report is largely included within the Western Protectorate, but in order to deal with all major basement-rock groups of the Protectorate, coastal areas of E.A.P. as far east as the longitude of Al Mukallā (about 49°08' E.) are included. Similarly, the structure of W.A.P. cannot be considered in isolation, and for this reason also, there is some overlap into E.A.P.

PREVIOUS WORK

Volcanic rocks of the southwestern region of the Protectorate have been the subject of investigation since McMahon (1883) recorded his observations about the lavas of Aden. Lloyd (1910) reported on volcanic (and sedimentary) rocks seen on a journey from Aden to Ad Dālī. Lamare (1930) referred to the younger volcanic rocks of both W.A.P. and E.A.P. in his discussion of post-Cretaceous vulcanism of the Red Sea and bordering countries. Recently, Irving and Tarling (1961) gave a limited description of samples of volcanic rocks from Aden Peninsula, taken in connection with paleomagnetic work.

The early studies of volcanic rocks are not matched in work on the geology as a whole. The main contributions to the geology of the Protectorate are as follows.

Little (1925) made a geological survey of the Al Mukallā area of E.A.P. during 6 months in 1919-20. In his account he included sections on stratigraphy and economic geology, and he very briefly described crystalline (basement) rocks. The account was accompanied by a 1:250,000-scale geological map of the area extending westward to the Wādī Ḥajr.

Lamare (1936) made some reference to the geology of W.A.P. in his "Structure Géologique de l'Arabie." His generalized geological map, at a scale of 1:11,000,000, is in need of considerable revision insofar as it applies to W.A.P. This work has greater value with reference to Yemen, although it appears that Lamare made a journey from the Yemen border to Aden via Ad Dālī.

Wissmann, accompanied by Meulen, made notable expeditions in E.A.P. and W.A.P. in 1931 and 1939, the results of which were published in 1932 and 1942. In the present report reference is made to some observations (Wissmann and others, 1942) on the crystalline (basement) rocks of W.A.P. No attempt was made to present a comprehensive description of basement rocks; and some general conclusions regarding the distribution of psammitic and metacalcareous rocks seem to have been based on too localized observations. Many significant observations on the structure of the Protector-

ate and surrounding regions were made, together with a small-scale geological map showing structural lines. The map represented a valuable advance on previous knowledge, but, as may be expected, was not accurate in detail.

Jaques, working for the Colonial Geological Surveys (now O.G.S.) made a number of traverses in W.A.P. and E.A.P. during some 18 months' work in 1951 and 1952. Economic mineral deposits were investigated, but apparently nothing of commercial interest was found. Little systematic mapping was done; nevertheless, a geological reconnaissance map (scale 1:1,000,000) was prepared from observations made in the course of travel. This constituted a valuable provisional map of W.A.P.—a region little known geologically. The map shows broad geological divisions but does not show structural lines or subdivision of basement rocks.

Most of the results of Jaques' work are embodied in unpublished notes. A very brief account of the geology of the Protectorate was published in 1954 (Jaques, 1954). Jaques observed that granitic rocks appear to be largely the result of granitization. His Cambrian and Ordovician rocks were not recognized in the recent survey.

By far the most comprehensive and detailed account of E.A.P. geology is that by Beydoun, whose work also overlaps into W.A.P. Beydoun made geological surveys of E.A.P. during six field seasons between 1953 and 1959, working for Iraq Petroleum Company and associated companies. Some of the results of this work, including geological maps, were published (Beydoun, 1960, 1964), or appeared in thesis form (Beydoun, 1961).

Much of Beydoun's work is on the stratigraphy of sedimentary rocks and on structure, but he has made a considerable contribution to the geology of the basement rocks of E.A.P. Some of the views tentatively expressed, in particular with regard to the relation of his Ghabar Group to the rocks of Wādī Gharīsh and the relation of Tha'lab Group volcanic rocks to both of these, do not accord with the views formed by the present authors. In this connection, it is emphasized that the reconnaissance nature of the work done does not permit categorical conclusions to be drawn.

Some account of E.A.P. basement rocks is contained in a paper discussing the correlation of various basement rock groups of this region with those of former Somaliland Protectorate (Greenwood, 1961).

PRESENT INVESTIGATIONS

Following photogeological mapping and fieldwork in basement areas of former Somaliland Protectorate, the Photogeological Division of O.G.S. was assigned the work of producing a reconnaissance map of the western part of Aden Protectorate. This region was little

known geologically, and apart from the small-scale provisional map prepared by Jaques, no geological maps were available. Through the cooperation of Iraq Petroleum Company, J. E. G. W. Greenwood of the Photogeological Division visited E.A.P. for about ten days at the end of 1958 and examined representative outcrops under the guidance of Z. R. Beydoun.

Photogeological interpretation started toward the end of 1959 and resulted in the production of a map covering approximately 31,000 square miles, including about 12,000 square miles of exposed igneous and metamorphic rocks. This map was completed in 1960, after some 18 months' work by one geologist.

PHOTOGEOLOGICAL SURVEY

The main object of the mapping was the delineation and subdivision of areas of igneous and metamorphic rocks in W.A.P., and also the plotting of major structural lines. The work was extended to cover the basement areas and associated sedimentary rocks of E.A.P. Interpretation was facilitated by previous knowledge of very similar rock types on the southern side of the Gulf of Aden, and by a preview of representative rocks in E.A.P.

Base maps were prepared from rectified photomosaics, from uncontrolled print laydowns, and from 1:100,000-scale topographic maps where these were available (Directorate of Overseas Surveys (D.O.S.) 554, Ser. K667). The aerial photographs interpreted were taken by the Royal Air Force mainly between 1955–57, at a flying height of about 40,000 feet, the resulting scale being approximately 1:80,000. These were supplemented by larger scale photographs flown by the Royal Air Force in 1952. Geological maps were initially produced at a scale of 1:250,000 and subsequently compiled at 1:500,000.

It was possible to distinguish between intrusive granite and granitized rock; and also to differentiate between extrusive rocks of various ages. The final scale of the map precluded the detailed differentiation of the complex metamorphic rocks; major sedimentary divisions were plotted.

FIELD SURVEY

During the months of November 1961 to February 1962 a field survey was made in W.A.P. and the coastal areas of E.A.P. as far east as Al Mukalla, about one-quarter of the period being spent in the latter region. The survey party comprised the authors accompanied by local staff.

The object of the survey was to appraise the economic mineral potential of the region and to check and amplify the photogeological mapping. Prior to fieldwork, traverses covering critical geological areas and

likely sites for mineral investigations were selected from the photogeological map. Both map and aerial photographs were used in the field.

During the survey an itinerary of some 3,300 miles was covered by Land Rover, and numerous foot traverses were made. Of some 300 rock specimens collected for intensive examination, about half have received detailed petrographic study. More than 300 samples were taken for geochemical analysis, and about 100 concentrate samples were obtained by panning material from selected wadis and beach sands. Specimens of economic minerals, including material potentially suitable for portland cement production, were taken for chemical analysis and assay, and large samples, mainly of granitic rock, were obtained for radiometric determination. A dionic water tester was used to ascertain the quality of water in springs and wells. A ratemeter was used during the survey without, however, any significant anomalies being detected.

GENERAL

It is apparent that geological knowledge of W.A.P stems to a considerable extent from photogeological work. Where tested in the field the photogeological map was found to be substantially correct, within the fairly broad framework adopted. Thus, further extrapolation on aerial photographs from the areas traversed is thought to be justified. Following concentrate examination and the collation of field observations and of results of petrographic study, data extracted from aerial photographs have been considerably amplified.

ACKNOWLEDGMENTS

The authors wish to express their appreciation and thanks to the following, who have contributed directly or indirectly to this account: To the Iraq Petroleum Co. for cooperation during a visit to E.A.P. in 1958, and in particular to Dr. Z. R. Beydoun for his able introduction to the geology of this area and general advice on conditions in the Protectorate; to the staff of the British Museum (Natural History) for paleontological determinations; to Mr. F. R. Gnauck of British Petroleum Co. Research Center, for palynological tests; to Professor F. Geukens of Louvain University and Dr. G. F. Brown of the U.S. Geological Survey for helpful discussions on geology of Yemen and Saudi Arabia, respectively; to the Aden Administration and members of the Aden Agriculture Department for assistance during the field survey, also to members of the Aden police and military escort; and to the Directorate of Overseas Surveys, Department of Technical Cooperation, for assistance in preparation of illustrations.

To Mr. E. H. Beard, Principal, Mineral Resources Division, O.G.S., and staff, acknowledgments are due

as follows: Dr. J. B. Allen examined and reported on petrographical specimens. The results are embodied in this account after interpretation in the light of field observations. Factual data on mineralogical composition and texture are referable to the petrographical report. The assignment to particular metamorphic facies is in most cases the responsibility of the present authors. Mr. J. A. Bain investigated and reported on panning concentrates; Mr. L. C. Chadwick made chemical analyses and assessed the suitability of limestone samples for portland cement manufacture; Messrs. D. R. Curry and P. J. Moore examined and reported on geochemical samples. In addition, economic minerals were investigated by the O.G.S. Mineral Resources Division. Data from all these sources are incorporated in this account.

Dr. N. J. Snelling, of the O.G.S. Age Determination Unit at Oxford University, provided data on rock samples from the Protectorate. Reference is also made to age determination by Dr. Snelling on rocks from former Somaliland Protectorate.

GEOGRAPHY

AREA, LOCATION, AND POPULATION

The total area of the Aden Protectorate is about 112,000 square miles. The area of the Western Protectorate has been estimated at some 19,000 square miles, but figures vary greatly since its boundaries are not all demarcated. The Western Protectorate is bounded to the west by Yemen, to the north by Yemen and the Rub' al Khālī, and to the south by the Gulf of Aden and the small area of Aden Colony.²

No census has ever been taken in the Aden Protectorate and figures are conjectural. The most recent estimate³ puts the population of the Western Protectorate at 350,000.

TRANSPORTATION AND COMMUNICATIONS

Surveys began in 1940 with a view to improving communications within the Western Protectorate, and a start was made on the three main trade routes leading from Yemen to Aden via Mufālis, Ta'izz and Ad Dālī, while at the same time improvements were made to the Aden-Lahj and Shuqrah-Aḥwar roads. Roads have now been constructed from Shuqrah to Lawdar, extending to Mukalla in the Eastern Protectorate along the coast, and inland to the Al 'Awāliq al 'Ulyā District and Bayḥan. Recently, new roads have been opened from Aden to Al Kirsh, from Ad Dālī to 'Awābil, and from Lawdar to Mukayrās, via

¹ The relatively recently formed Federation of South Arabia includes former Aden Colony and the Al Wajjil States (formerly of the Eastern Protectorate) and covers about 35,000 square miles.

² Aden report for the years 1947 and 1958, London, H.M. Stationery Office, 1961.

the Thirah pass. Bituminized roads cover 110 miles in Aden Colony, and in the Abyan area gravel roads link the main centers of population.

Away from the coastal towns no road is of good quality, and the cost of maintenance of motor vehicles is excessive, owing to the nature of the surface of the roads and their commonly steep gradients. In many places it is possible to use dry wadi beds as motorways, although vehicles with four-wheel drive are highly desirable. In the gravel desert of, for example, Jaww Kudayf, motoring in any direction is feasible, and in sand deserts such as the Ramlat as Sab'atayn, routes can usually be found around and between dune chains. The motor route across the Ramlat as Sab'atayn from Nasr to Jabal ath Thaniyah continues to Mar'ib in Yemen, and probably coincides with the old incense-caravan road.

The camel caravan is the principal method of transport and a considerable proportion of the population is engaged for its livelihood in the carrying trade. Donkeys are used for carrying such articles as firewood and fodder, and are more generally used for riding. All settlements in the Protectorate are linked by caravan tracks: the most important routes are those leading from Aden to Yemen through As Subayhi, Al 'Abdali, Al Hawāshib, and Al Amiri territories, and those used by caravans from the Yāfi Mountains, the Kawr al 'Awāliq, the Kawr al 'Awādhil, and the coastal route connecting Aden with Shuqrah, Aḥwar, and Mukalla.

The Royal Air Force maintains a large airbase at Khormaksar (Aden) that is also used by the local Aden Airways Ltd., which provides a regular schedule of flights to a number of towns and intermittent or charter service to others.

CLIMATE

The Protectorate experiences temperatures in the higher range, the extremes being accentuated by the variety of its physical features. There is less range of temperature in the coastal areas than in the interior, but the former have a humid atmosphere and are liable to heavy dews and morning mists. The highlands have a wide range of temperatures between summer and winter, and the diurnal range may be great.

The hottest months are May to September; the peak is in June and July, when temperatures of more than 100 °F are frequent. Temperatures of 130 °F are reached in some localities. During the winter months low temperatures of 34 °F were measured in the interior by the authors, and frost has been reported; along the coast however, nothing less than 60 °F has been recorded. (See table 2.)

TABLE 2.—Temperature and rainfall records

[Temperatures recorded at Aden. Period 1931-1943]

Month	Temperature (°F)		Mean rainfall (in.)			
	Highest	Lowest	Khormaksar (Aden), 123 feet above mean sea level (6-yr period)	Baybān, 3,500 feet above mean sea level (3.4 yr period)	Ad Dāir, 4,575 feet above mean sea level (6-yr period)	
January.....	92	65	Less than .1	0.2	0.6	
February.....	91	61	Less than .1	.3	.3	
March.....	96	67	Less than .2	.4	.4	
April.....	101	69	Less than .1	1.2	1.2	
May.....	102	70	Less than .1	1	2.1	
June.....	109	73	Less than .1	.2	.8	
July.....	109	70	Less than .1	3	3.9	
August.....	107	63	Less than .1	12.1	4.7	
September.....	102	71	Less than .1	1	2.1	
October.....	101	70	Less than .1	0	.2	
November.....	97	68	Less than .1	0	.2	
December.....	93	64	Less than .2	0	.2	
Total.....				5.2	16.2	

¹ In 1 year up to 8 in. fell in this month.

The prevailing winter wind in the Gulf of Aden is the easterly monsoon which swings southeasterly in the straits of Bāb al Mandab; in May the humidity sometimes rises and the winds are variable. From June to September they blow steadily from the west into the main current of the southwest monsoon in the Arabian Sea and bring occasional violent storms. In the interior the winds are to some extent affected by the hot center of the Arabian peninsula (see p. C9). A dry northerly wind which is known in Aden as the *kawi* (hot iron) blows occasionally in the Gulf of Aden during the southwest monsoon; in the interior this wind is called *kharif* or *habub* and usually occurs in the afternoons.

On the coastal plains and in the desert areas, sandstorms are fairly frequent and dust devils and mirages are common. Mists and haze are usual in the summer months, so visibility is poor.

Rainfall is irregular but more frequent in the winter months, except in the hilly interior. The total annual rainfall probably reaches 20 inches in parts of the interior, but owing to the very high rate of evaporation, added to the heavy demands for irrigation, only one perennial river reaches the coast (Wādī Ḥajr in the Eastern Protectorate). In the coastal areas the average annual rainfall is less than 2 inches; in exceptional years it has exceeded 5 inches, but much of this may fall in a single storm. (See table 2.)

VEGETATION

Data presented in this section are drawn largely from British Naval Intelligence Division's Geographical Handbook B.R. 527, titled "Western Arabia and the Red Sea," published by H.M. Stationery Office in 1946.

The plant distribution is conditioned by the incidence of rainfall and by the geology, topography, and drainage. The geographical range is more affected by rainfall than by temperature. On a smaller scale the micro-

climate is of great significance and again is largely controlled by orographic factors such as relief and whether slopes are of north or south aspect, the temperatures of south-facing slopes being consistently higher than those facing north.

The vegetation of the coastal plain is largely determined by the topography because at many points, particularly in the Eastern Protectorate, the mountains reach the sea. The inner coastal plain carries a vegetation of open orchard type dominated by the long-thorned acacia (*Acacia spirocarpa*). This is a deep-rooting tree which taps perennial ground water and is largely independent of the local rainfall. Its green foliage persists throughout the year but may be reduced in the drier months.

In the hollows and silty pans between sand dunes, tussock grass (*Panicum turgidum*) and *Cassurus hirsutus* are the dominant grasses. Halophytic vegetation marks the beach fringe and the sporadic salt pans. The coconut palm is found in a narrow strip near the coast, from a point west of Aden to about the mouth of wadi Al Masilah in the Eastern Protectorate. There is a particularly luxuriant growth of doum palms (*Hyphaene thebaica*) and *Suaeda* on the sand dunes between Ash Shaykh 'Uthmān and Aden Colony, particularly on the north shore of the Bay of Aden, and at Khormaksar. The commonest plant at Aden is a large kind of mimonette (*Reseda amblycarpa*), and the most conspicuous, a bushy green caper (*Capparis galeata*); next commonest are a large herbaceous spiderwort (*Cleome brachycarpa*) and the acacia (*Acacia Edgeworthii*).

A euphorbia (*Euphorbia schimperi*), the rummid of the Arabs, forms leafless intricately branched shrubs with pale-green fleshy branches. The fleshy trunks, naked branches, and fragrant rosy flowers of the "adan" bush (*Adenium arabicum*) make it conspicuous on the crags around Aden. This plant also occurs as high as 3,300 feet and more in the mountains of the Western Protectorate.

In the coastal wadis the acacia is the commonest tree, being replaced in drier wadis by the nebu (*Zizyphus spina-christi*); in sufficiently watered wadis the date palm is found. Frankincense grows in some of the smaller inland wadis, but the dominant tree is the tamarisk (*Salvadora persica*), particularly in sandy places. The ariata (*Conocarpus erectus*) is also found in certain wadis; it is frequently a constituent of coastal mangrove formations.

The barren elevated jol of the Eastern Aden Protectorate carries little vegetation, but species of aloe and the dragon's blood tree (*Dracaena serrulata*) have been noted. In mountainous areas, close to the Yemen border, tall tamarisks are common; and in sufficiently watered wadis, clumps of a dwarf date palm, reputed

to be *Phoenix reclinata*, and a low scrub of wild indigo (*Indigofera*) occur. In moister rock clefts, ferus, a horsetail, and selaginella have been reported.

Myrrh, as frankincense, is found in many parts of the Western Protectorate. This is a gum produced by stunted trees or shrubs of the genus *Commiphora*, and more than 50 years ago was collected in Faqlī country, northeast of Aden.

The sand deserts, such as the Raml as Sab'atayn, are almost entirely devoid of trees and the vegetation consists mainly of grasses, such as artā (*Calligonum comosum*) and *Aristida plumosa*, with rare *Cyperum* sp. After rain, the sedge, *Fagonia glutinosa*, is the first to appear, followed by alab (*Calligonum* sp.), and later *Dipterygium glaucum* and occasionally *Tribulus macropterus*.

TOPOGRAPHY, MORPHOLOGY, AND DRAINAGE

The western part of Aden Protectorate comprises four well-marked physiographic zones, which are, from south to north:

1. The coastal plain.
2. The ramped plateaus composed of Cretaceous to Eocene trap sheets in the west, and the crystallines of the Kawr al'Awādhil and Kawr al'Awāliq in the east.
3. In the north of the Protectorate, the sand desert of the Raml as Sab'atayn and the gravel plains of the Jaww Kudayf and the Jaww Mulyas.
4. In the extreme northeast, the plateau (jol) of Mesozoic and Tertiary sediments which, north of the Wādī Haḡramawt, dip northward under the sands of the Rub'al Khālī.

COASTAL PLAIN

The present coastal plain, bordering the Gulf of Aden, is about 30 miles wide at its greatest extent north of Aden. To the east it narrows, and at Ra's ar Rujaymah older volcanic rocks reach the sea. The plain is a depositional feature superimposed on a marine bench cut in Oligocene and Miocene sediments and crystalline rocks subsequent to the last movements of the rift fault blocks. The coastal plain has been built up in stages from alluvial material brought by innumerable short wadis which drain the ramped mountain ranges of the hinterland, as well as by the few major wadis, such as Wādī Tuban which rises in Yemen, Wādī Banā, Wādī Hasan (which formed the Abyan delta), Wādī Aḡwar, and Wādī Mayfa'ah.

The finer grades of alluvial material occurring toward the seaward edge are redistributed by wind and sheet wash. A sorting action results and particles of the finest grade are washed into silty pans or removed by wind; sand-size particles are built up into an extensive

series of dunes which are alined according to the regional and local wind regimes. Textbook examples of barchans and seif dunes can be found, together with transitional types resulting from diurnal changes in wind direction, from deflection of windstreams by rock masses and local areas of hot sand, and from occasional storms.

Winnowing by the wind leaves in situ the heavier alluvial material of fine gravel and of cobbles and boulders, which may reach 12 inches in diameter; older such deposits are frequently found as long ridges trending seaward and elevated slightly above the general level by removal of the finer flanking material. In many areas these gravel trains have coalesced and built up extensive stable flats which now carry an open orchard type of vegetation dominated by *Acacia* sp. They are frequently dissected by more recent, narrow gullies which may originate either on the high ground behind the coastal plain, or locally on the flats themselves.

Toward the mountain front, the material becomes coarser and poorly sorted. Remnants of coarse-gravel flats at various elevations above the present plain were observed at Al 'Anad, north of Aden, and at other points along the coast near the foot of the mountains. Gravel on the highest flats has developed a very dark patina and contains little interstitial material of finer grades; cemented layers of calcareous material sometimes produce a stratified effect. Intermittent Pleistocene to Recent uplift along the rift faults is probably responsible for these stepped terraces.

Lavas of late Miocene or Pliocene to Recent age overlie the coastal plain at various points, namely Jabal Kharaz, Aden Colony, east of Shuqrah, and near Bi'r 'Ali. Associated with them are tuffs and ash together with numerous cinder cones which rise to about 320 feet in height. The extinct crater of Kharif Shawrān, near Bi'r 'Ali, contains small blocks of ultrabasic rocks, including dunite, and its central depression holds a saltwater lake which is fringed with mangrove trees and is in hydraulic continuity with the sea. The recent age of the volcanicity is attested by the fact that the lavas themselves have infilled certain wadis and are interbedded with, or rest upon, alluvial deposits. These lavas form the sea cliffs at Aden and reach the shore in the Bi'r 'Ali-Balhāf area.

In the Eastern Protectorate between Ra's ar Ruja-yimah and Burūm, a coastal plain is not developed and cliffs have been cut in basement rocks behind narrow beaches.

RAMPED PLATEAUS

Behind the coastal plain the country has a pronounced east-northeast grain, with local modification, largely due to faulting associated with the Gulf of Aden rift;

this has determined the primary pattern of drainage and is responsible for the straight line of many wadi courses. The strike of basement foliation has had a subsidiary, albeit important, influence on the secondary drainage.

Northward from Aden the general level of the country rises through inclined and dissected steps toward the ramped plateau of Jabal Jihāf (near Ad Dālī) at about 8,000 feet. Farther north, in Yemen, the trap lava sheets, where unaffected by faulting, form an even plateau more than 9,800 feet in elevation. This corresponds broadly to the highest levels in the Kawr al 'Awādhil, seen typically at Mukayrās, and represents shallowly dissected remnants of a Paleozoic erosion surface which was subsequently faulted and folded mainly during the Tertiary earth movements. In the Kawr al 'Awāliq and Kawr al 'Awādhil ranges, ramp fault blocks that are normally south dipping but locally north dipping and that involve basement and Mesozoic rocks present a series of knife ridges on which dip slopes carrying consequent streams are actively downcutting. Most strike streams appear to be fault controlled, and headward erosion has resulted in capture by a few dominant streams such as Wādī Banī (Ḥasan) and Wādī Dayqah (Aḥwar), which demonstrate both north and northeast flowing components.

In the northern part of the Kawr al 'Awāliq and Kawr al 'Awādhil, the drainage is to the north. In their upper reaches the wadis are narrow and stepped, but their lower courses are heavily covered by alluvium where they debouch into the Jaww Kudayf. In this region, wadis from the Niṣāb-Bayḥān mountains and from Yemen swing northeast and east toward the line of the Wādī Ḥaḍramawt; west-flowing wadis such as Wādī Jirdān which have cut back into the escarpment forming the western limit of the jol also turn northward on entering the Jaww Kudayf at 'Iyādh. Their courses can be traced for some miles out from the mountains (for the Wādī Bayḥān, 40-50 miles) but there appears to be no present flow of surface water; it is inferred, however, that there is a subterranean seepage into Wādī Ḥaḍramawt along the former wadi courses.

This older drainage, in a hinterland which has been less affected by the Tertiary earth movement, shows a development of excessively wide flat-bottomed wadis, the width of which bears little relation to the present, or probably former, erosive ability of the intermittent flow of water. Wādī Durā is almost 3 miles wide east of Niṣāb (Anṣāb), and Wādī Markhah, between 3 and 6 miles wide. The processes of pedimentation and scarp retreat appear to be largely responsible and well-formed rock pediments flank many of the major wadis (fig. 1). This is a fairly general character-



FIGURE 1.—Rock pediment veneered with coarse debris, near Al Khabr.

istic of Aden Protectorate wadis and some are stepped, the present wadis being 65-100 feet below the level of the highest pediment. Clearly recent uplift has occurred on more than one occasion, inducing new cycles of erosion.

In metamorphic terrain, valley floors tend to open out, in places, into intermontane basins which may provide considerable areas of cultivable land. These basins are normally the result of differences in lithology; some such basins, however, have a more complex origin. The extensive plain around the town of Lawdar, for example, is limited on its northern side by the Thirah escarpment, which rises steeply to more than 6,500 feet above sea level. This plain appears to have originated as a fault scarp which has probably retreated from its original position. There is evidence that faulting has also occurred on the southern side and that this plain is, in fact, a small structural trough.

The widespread accumulations of alluvial material point to a time of moister climatic conditions, when the carrying capacity of the wadis was greater. This material, ranging from boulder to silt size, is now seen in terraces and outwash fans, which are a pronounced feature of the landscape. If the terrace deposits date

from possible Pleistocene pluvial periods, the present downcutting phase of the wadis results from the subsequent decrease in the ratio of waste load to water, and from the steepened slope of the prealluvial cones.

In areas where sediments and basement rocks are exposed, the morphology is closely related to the geology. Many granitic rocks give rise to areas of low relief and rounded form, and can be delimited on aerial photographs by these characteristics. Through exfoliation in concavo-convex shells, irregular masses and angular blocks resulting from jointing are reduced to rounded forms. White kaolinitic weathering products, together with residual quartzitic material, impart a light tone to aerial photographs of these areas. Younger, or post tectonic, granites are in many places outstanding, and the spinelike plugs east of Mudia are a good example. Certain schistose rocks tend to form sharply serrated mountains with rugged crests; some soft schistose rocks produce a thick mantle of waste having little fresh rock exposed and thus having rounded contours; in areas of more active erosion, a badland topography results. Intrusive dikes are common and result in narrow, elongated, and elevated ridges; these give a ribbed

effect to the landscape in the Mukayrās area. Well-bedded limestones, capping fault blocks or flat-lying in the jol, are distinctive on aerial photographs as associations of level stripped surfaces.

To the north of the Kawr al 'Awāliq and Kawr al 'Awādhil the country falls away to the plains of the Jaww Kudayf and the Ramlat Sabas'atayn at about 3,000 feet above sea level. No active drainage exists, the main physical features being the extensive system of sand dunes.

SAND DESERT AND GRAVEL PLAIN

The center of the Arabian Peninsula is occupied by a vast area of gravel plains, with sand arranged in a variety of organized patterns as individual dunes, dune chains, and massifs. The main sand region is the famous Rub' al Khālī, which covers almost a quarter million square miles, extending from just north of the 16th parallel to about the 24th parallel and from meridian 45° E. to almost 57° E.

South of the Rub' al Khālī there is an extensive gravel plain, on the order of 150,000 square miles in size, the southern part of which lies in W.A.P. This is bounded in the east by the limestone jol which runs north from 'Ataq to Shabwah and Al 'Abr and curves northeast and east into Dhofar. In the south lie the Niṣāb-Bayḥān mountains, of mainly Precambrian rocks, which swing round to the northwest and north into Yemen and Saudi Arabia.

The plain is divided into three regions by the dune sands of the Ramlat as Sab'atayn and by As Sawdā' scarp, which run west and north, respectively, from Al 'Abr. To the north of the Ramlat as Sab'atayn and separating it from the Rub' al Khālī is the Jaww al Mulays. Southeast of the Ramlat as Sab'atayn, between it and the Niṣāb-Bayḥān mountains, is the Jaww Kudayf, and the smaller Jaww Hādhī lies to the east of the As Sawdā' scarp (Bunker, 1953).

The routes from 'Ataq to Niṣāb and from 'Ataq to Bayḥān cross the Jaww Kudayf, which is level at about 3,000 feet above sea level. Surface particles in the size range of fine to medium sand have been largely removed by the wind; the resulting pavement is composed of fine gravel and coarse sand, the grains averaging about 1 millimeter in diameter. Figure 2 shows the size distribution in the first inch of depth, the finer grains, approaching 0.1 mm in diameter, coming from below a depth of one-half inch. The microrelief includes low parallel or subparallel ridges of coarser gravel which do not appear to be continuous over long distances. Associated with these are a few even coarser gravel particles as much as 30 mm in diameter, some of which show faceting, due to sandblast effect, and similar orientation of the dreikanter, which points to a long undisturbed period in situ. These gravels may have originated through the sorting action of sheet wash on alluvial material brought from the Yemen-Bayḥān mountains during a former wetter period (a Pleistocene

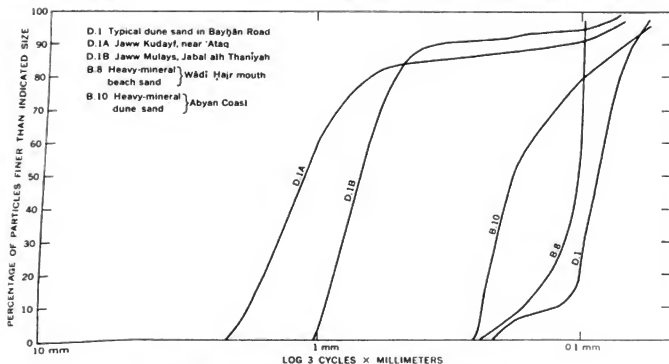


FIGURE 2.—Cumulative curves of sand samples from Aden Protectorate.

pluvial?). Bunker (1953) described wadi channels, as much as 2 miles wide and 20 feet deep, and heavy alluvial gravels occurring in the northeastern part of the Mulays plains.

On the eastern side of the Jaww Kudayf, isolated low hills and mesas, such as An Naṣr and Shabwah, stand as outliers of Mesozoic rocks, together with the salt domes of Miḥ Kharwah and 'Iyādh. The hills of the limestone jol are flanked by extensive rock pediments which are covered with a thick veneer of limestone boulders and coarse gravel, often lightly cemented into fairly stable terrace selvages. Again, the present cycle of erosion is not producing gravel deposits of this type, which therefore probably belong to a former more humid period. West-flowing wadis from the jol veer northwest and north toward the Wādī Ḥadramawt on entering the Jaww Kudayf, and it would be of interest to confirm that there is in fact an underground flow of water in this direction and to determine whether a permanent water table exists in this area (see "Water Resources" section, p. C82). It is possible that the former hydraulic network has now ceased to function and the control exercised by a universal base level is lost and replaced by independent bolsons of centripetal drainage.

The extremely level nature of the Mulays-Kudayf plain suggests a pediplain and an origin by pedimentation—the few outcrops of Precambrian rocks, such as Jabal ath Thantyah, representing inselbergs. If this is so the plain probably represents an exhumed surface, as the basement rocks exposed beneath the Mesozoic and Tertiary sedimentary rocks to the southeast of 'Ataq were also base levelled in pre-Mesozoic times—although not to the high degree now apparent in the western plains. These sedimentary rocks at one time overlapped onto Precambrian basement rocks in the Yemen-western Saudi Arabia area, and the further period of planation followed the stripping back of the sedimentary cover. This process of eastward retreat and the origin of the western plains have been variously attributed to headwater erosion and river capture (Bunker, 1953), and to uplift of the basement rocks in the west associated with the Red Sea rift block faulting (Wissmann and others, 1942).

At Al 'Ubaylāt, the Bayhān track enters the Ramlat as Sab'atayn, a sand-dune area lying south of the 16th parallel. It is 50–70 miles wide at its western end near the Yemen hills, and tapers to about 10 miles wide where it enters the Wādī Ḥadramawt. Here the dunes lose height and lateral extent, wedging out as isolated patches of dunes some 3 miles in width near Shibān. The Ramlat as Sab'atayn comprises a series of mainly parallel but sparsely convergent sand-dune chains (urq) separated by narrow flats of gravel, silt, or gypsum

(shuq). Many of the individual ridges persist for several miles, their orientation swinging round from almost east in the An Naṣr area to north-northeast near An Naqūb, where Wādī Bayhān emerges from the mountains. Near Shabwah and An Naṣr, east-west routes have been used to cross the northern side of the Ramlat as Sab'atayn, and the present camel track, which was traversed by Land Rover as far as Arayn and Jabal ath Thantyah, is probably one of the old incense routes from the Ḥadramawt to Ma'rīb in Yemen and to western Saudi Arabia. Several wadis flow east from the Yemen hills and disappear in the sands, but Wādī Bayhān persists for about 45 miles out from the mountain front, crossing the Ramlat as Sab'atayn to emerge onto the Jaww Kudayf Al 'Ubaylāt. It provides the only motorable route into Bayhān.

Outcrops protrude through the dunes at numerous points: a small cluster of Precambrian rocks occurs in the Jabal ath Thantyah area and Mesozoic rocks appear at Arayn; also there is a salt dome some 40 miles northeast of An Naqūb. Blocks of basalt and pumice bombs were found occasionally in the interdune flats, but their source is uncertain; they probably originate from the Yemen mountains in the Ma'rīb area.

Apart from the few irregularities which are rapidly being reduced by exfoliation to the general level of the sand floor—where the rock is screened from the great diurnal variations in temperature—bedrock relief appears to be low. The orientation of the sand dunes must therefore depend on the wind velocity, direction, and frequency. Monsoon winds in the coastal areas are southwesterly in summer and southeasterly in winter, but local conditions within the peninsula of Arabia must be expected to cause some modifications. Heating up of the Rub' al Khālī sands in early summer may well cause an inflow of winds from the surrounding mountains. This appears to have contributed to purely local patterns in the dunes of the Ramlat as Sab'atayn, where the long axes of the dunes point away from the landmass at Bayhān and near An Naṣr (fig. 3); such a direction is opposed to the general Rub' al Khālī trend (fig. 4). The general trend is common to the other four great sand regions of the world, namely, Australia, Egypt-Libya, and the two ergs of the western Sahara. In all these the main dune ridges are affected (1) by the westerly storm winds and (2) by the trade winds. As the tropics are approached the westerlies tend to decrease, and the trades begin to dominate. The result is a 90° sweep round, so that the dune ridges end by approaching the equator from the northeast and southeast. Bagnold (oral commun., 1964) has suggested that the Ramlat as Sab'atayn change of direction, in the opposite sense, might be

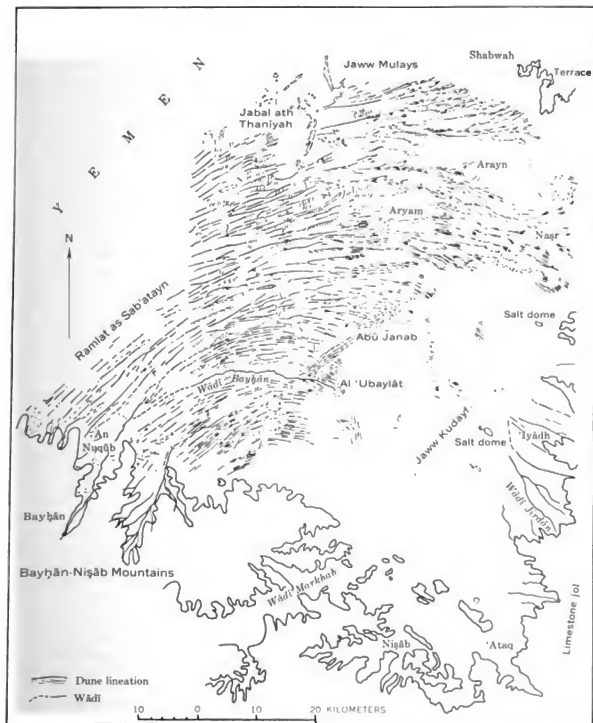


FIGURE 3.—Ramlat as Sab'atayn sand desert, southern Arabian Peninsula.

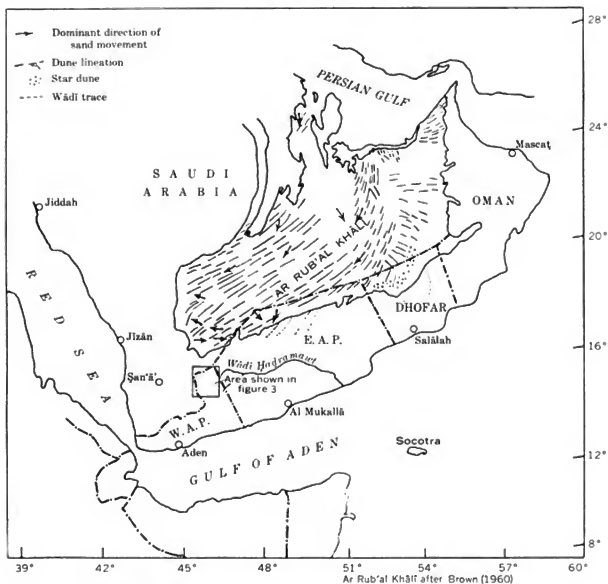


FIGURE 4.—Southern Arabian Peninsula showing Ar Rub'al Khali sand desert.

explained by the effect of the Yemen mountains in sheltering the area from the westerlies, this sheltering being less to the north than in the south; at lat 15° N. the northeast trade winds dominate, but farther north the westerlies dominate.

During a brief visit to Jabal ath Thaniyah the following wind directions were noted on February 1, 1962:

7 a.m.	North-northwesterly
12 noon	South-southeasterly
4 p.m.	Easterly
8 p.m.	Northerly

According to the local Bedouin the main wind directions are northerly in the mornings and southerly later in the day. The northerly winds are evidently

the stronger since the slip faces were to the south or southeast, but the effect of southerly winds would be to check the lateral movement of the dune chains.

Bagnold (1938) stated that the sand-driving effect of wind is a cube function of the wind strength, and it is therefore not sufficient to know the relative number of occasions on which the wind blows from each point of the compass, since a few storms during the course of the year may dominate the wind regime as it affects dune formation and movement. The dune chains may be orientated in the direction of the main sand stream although this is at right angles to the two commonest wind directions in the Jabal ath Thaniyah area. In general, the northerly wind is the stronger

and has resulted in asymmetrically shaped dunes having gentle slopes on the northern side and slip faces to the south and southeast. That some lateral movement of the whole dune chain takes place in this direction is attested by the fact that during the authors' visit a storm some miles away produced fresh winds which moved the foot of a dune slip face, adjacent to the camp, almost 1 foot in a few hours. The observed diurnal reversal of wind direction is an important factor tending toward stability and is a check on dune migration. The dune chains, between which Wādī Bayhān makes its way, also show evidence of movement in the direction at right angles to their long axes. On the western and northern sides of the wadi, bushes and discontinuous lines of artā (*Calligonum comosum*), now buried in sand to varying degrees, mark former channels of the wadi, which has been pushed progressively to the east and south by movement of the dune chains.

The main direction of sand movement is difficult to assess. In the Wādī Bayhān area the dune chains wedge out in the mouths of the larger wadis and approach within a few hundred yards of the mountain foot, but touch it at one or two points only. There is no extensive piling of sand against the mountains as would occur if the bulk of the sand were moving in that direction. The mountains would deflect wind blowing toward them and the resulting turbulence would be expected to distort the dune pattern; it is clear from aerial photographs that the dunes diminish in size and fade out gradually as the mountains are approached. However, it is unlikely that the main dune movement is in the opposite direction, since the question of sand supply is introduced and no evidence was seen of the formation and movement of sand-size material in the mountains to the southwest.

That two wind components are probably necessary for dune formation, as suggested by Bagnold (1938), is shown by the dune pattern round Abū Janab immediately north of Al 'Ubaylāt. Here a small set of dunes lies at right angles to the Ramlat as Sab'atayn dune trend and must be a purely local phenomenon which results from one wind becoming dominant over the other in this particular area. It may also be the explanation, on a much larger scale, for the dunes to the north of Dhofar, shown in figure 4, which lie at right angles to the Rub'al Khālī trend. Another local phenomenon which does not appear to have been described before was observed to the east of An Nuqūb in Wādī Bayhān; this is a series of small quadrant-shaped dunes restricted to a narrow zone on the eastern flank of a complex dune chain, sited in the mouth of Wādī al Jif'iyah (fig. 5). The dunes rest on a pavement of coarse gravel and are of constant size, about 33 feet wide and 3-4 feet high; two slip faces had been



FIGURE 5.—Quadrant-shaped sand dunes. Wādī al Jif'iyah.

developed by northeasterly and northwesterly winds of equal strength, which caused a resultant movement of the dune system to the south. The rate of movement could be measured, at about 1 foot a year, against old Land Rover tracks, preserved in the pavement, over which some of the dunes had advanced.

PLATEAU

In the northeast, between the 47th and 48th parallels, the flat-lying or gently folded Mesozoic and Tertiary sedimentary rocks form an extensive plateau, or jol, its western boundary with the Jaww Kudayf being marked by a steep escarpment with a boulder- and scree-covered pediment. It is a tableland capped by mesas and cuestas of Eocene rocks, over 4,900 feet in elevation and deeply incised by a network of drainage that flows mainly into Wādī Haḍramawt. Scarps bounding the mountains and flanking incised wadis are commonly steep and of considerable height. Massive sedimentary rocks give rise to sheer walls, and where bedding is pronounced and there is an alternation of resistant and less resistant beds, steplike benches occur.

Wādī Haḍramawt, as well as many of the main wadis, has cut down through 1,000 feet of sedimentary rocks to expose Cretaceous beds. Tributary wadis with less erosive power are commonly arrested at various stages of downcutting by relatively more resistant beds and widen their floors at these levels by lateral planation. Extensive surfaces are formed in this way, often carrying small buttes and mesas as evidence of their mode of origin. These local planation surfaces are commonly veneered with a "pavement" or thin layer of residual gravel which is poorly sorted and often angular; such layers originated by flaking or

cleaving from the underlying limestone and developed in the course of time a black patina of desert varnish. Over such surfaces, at other points, deflation is active in removing the finer particles of clay, silt, and sand size, leaving shallow depressions and ridges of harder material often carrying dreikanter and other faceted stones. After the wadis have cut below these surfaces, the hard limestone bands continue to influence the morphology in forming repeated free faces which contribute debris to talus cones on the flanks of the wadis.

GEOLOGY

BASEMENT-ROCK UNITS AND PETROGRAPHY

The term "basement" is applied to all rocks older than the unconformable cover of Jurassic and younger sedimentary rocks. An exception to this is made for certain post tectonic granites of Late Cretaceous or Tertiary age, which are conveniently considered with other earlier granites.

Statements concerning numbered specimens refer to petrographical data derived from examination of thin sections.

OLDER GNEISS

The oldest rocks exposed in the Protectorate are represented by orthogneiss of granitic and granodioritic composition. Rocks assigned to this older gneiss group give no indication of intrusive relations with adjoining rocks, and field examination has not revealed the presence of included metamorphic rocks, either partially migmatized or otherwise. The older gneiss group appears to be distinguishable from later syntectonic granite by the presence throughout the rock body of well-marked foliation (which may be absent from parts of the syntectonic granite), by the absence of gradational contacts with metamorphosed surrounding rocks (which the gneiss is assumed to underlie), and by the absence of feldspathization in such adjoining rocks.

Outcrops of older gneiss have been recognized near Tor al Baha in the southwest of the Protectorate, in the Sa'id area, and about 6 miles east-southeast of Nişab.

In the Tor al Baha area the gneiss is of two main types, the dominant gneiss being a fine- to medium-grained rock with porphyritic feldspar augen, which is cut by more coarsely foliated gneiss. In specimen A43, described as a banded garnetiferous biotite-hornblende-quartz-feldspathic gneiss, much of the abundant feldspar is oligoclase, but sparse prominent phenocrysts of microcline perthite occur. Yellow or colorless garnet is infrequent. The appearance of the rock suggests a deformed granodiorite (or quartz diorite) and supports the assumption that syntectonic granitic invasion resulted in alteration of older gneiss. In this

connection the presence of feldspathic porphyroblasts of potassic composition, perhaps due to granitization, is relevant.

A limited exposure of older gneiss occurs on the northeast periphery of the Sa'id granite, some 4½ miles north of Yashburn. A specimen of this rock (A134) shows a granite gneiss of abundant quartz, tending to be granulated, late microcline, and oligoclase. Petrographic examination suggests an origin through deformation of a previous granite. Since in the Sa'id area syntectonic granite is known, it is likely that a later invasion of this rock affected the earlier gneiss and possibly accounts for the late appearance of microcline in the gneiss.

In the Nişab area a granodiorite gneiss of quartz, andesine, hornblende, and clinopyroxene forms a small outcrop. Hornblende and clinopyroxene tend to occur in bands. The foliation of the gneiss appears to be primary. In this rock no evidence of shear or cataclasis, apart from slight strain effects in the quartz, is seen. This is perhaps difficult to reconcile with the postulated early age of the gneiss unless this formed a mass resistant to subsequent tectonic stress.

The evidence is not strong but is thought adequate to warrant a tentative separation of the older gneiss group from later basement rocks.

ADEN METAMORPHIC GROUP

The term "Aden Metamorphic Group" has been introduced to refer to a group of metamorphic rocks which makes up a large part of the Protectorate basement assemblage. The group comprises metamorphosed sedimentary and mafic igneous rocks with some volcanic representatives.

The original sedimentary deposits included types ranging from coarse- to fine-grained arenaceous rocks to fine argillaceous deposits. Rocks representing variable admixtures of argillaceous and arenaceous material are common. Calcareous-dolomitic phases were well marked and common; they resulted in limestones and dolomitic limestones, many of considerable purity, and in calcareous shales and grits.

No horizons of unconformity have yet been established in the Precambrian metamorphic rocks of the Western Protectorate, and in the absence of evidence to the contrary the rocks are considered to be members of one group, excepting only the older gneiss (described earlier). Rocks of the Aden Metamorphic Group are described under four main headings, namely pelitic, psammitic, metacalcareous, and metamorphosed mafic igneous rocks.

PELITIC ROCKS

Metamorphic rocks derived from argillaceous and impure argillaceous sediments form a component of

the Aden Metamorphic Group widely distributed throughout W.A.P. and the older basement-rock areas of E.A.P.

At As Sufāl, Wādī Ḥabbān, garnet-muscovite-biotite schist is interbanded with quartzitic and metacalcareous rocks and demonstrates metamorphism in the higher part of the green schist facies. In a specimen of this rock (A129) polymetamorphism is shown by the crumpling of an original schistosity, by the presence of two generations of quartz and mica, and by the bending of mica microporphyroblasts. In the same area are garnetiferous biotite-epidote schists, in which the presence of oligoclase plagioclase indicates a higher grade of metamorphism in the lowest part of the almandine-amphibolite facies. The breakdown of garnet, which lacks crystal outlines and shows marginal alteration to chlorite, suggests retrograde metamorphism. The specimens from As Sufāl were taken from a belt of steeply dipping metamorphic rocks extending from As Sufāl northwest to near 'Ataq. The presence of polymetamorphic rocks and of higher grade metamorphism in rocks of this belt makes it improbable that low-grade quartz-chlorite and chlorite-epidote schists, well developed in this belt, could represent an upper less metamorphosed division of the Aden Metamorphic Group.

Garnet-epidote-biotite schist containing abundant sodic oligoclase crops out in a locality some 5 miles south-southeast of 'Ataq, where it flanks an intrusion of little altered gabbroic rock considered to be of later date. The schist is metamorphosed in the almandine-amphibolite facies. Prisms of actinolitic amphibole tend to be associated with biotite in this rock, but they appear to be too rare to justify assumption of an igneous origin for the schist. The possibility of admixture of volcanic material in the original sediment is indicated.

In the Wādī Gharish area of E.A.P. quartz-muscovite and quartz-biotite schists occur in an assemblage of basement rocks comparable in lithology and metamorphic state with the basement of W.A.P. On the right bank of the wadi, about 1 mile below the Jurassic limestone outcrop of Jabal Suwayqah, an outcrop of garnet-staurolite-biotite-quartz-muscovite schist (A229) shows the highest grade of metamorphism determined in pelitic rocks of the Protectorate, that is, metamorphism in the lower subfacies of the almandine-amphibolite facies. Relic bedding in this rock is clearly marked by layers of garnet- and biotite-rich bands. (See fig. 6.)

Apart from the localities mentioned above, pelitic and semipelitic rocks occur in many areas of the Western Protectorate, mainly as biotite, biotite-muscovite, and quartz-biotite-muscovite schists. Metamorphism varying from that appropriate to the quartz-albite-epidote subfacies of the green schist facies to that ap-

propriate to the lower almandine-amphibolite facies is shown. Polymetamorphism is indicated in some of these rocks. Localities in which these pelitic rocks have been recorded include 'Awābil, Kīrsh, Wādī Raybān, Mūdiyah, Bayḥān, and Wādī Aḥwar.

PSAMMITIC ROCKS

Psammitic rocks are in numerous localities and their distribution is such as to suggest that they are not confined to any particular horizon of the basement succession. The thickness of individual bands, which like those of other rocks of the Aden Metamorphic Group are commonly steeply dipping to vertical, was estimated to range between 30 and 100 feet.

The original sediments, from which most of the psammitic rocks were derived, appear to have been either a quartz-feldspathic or an arkosic type. Less common and thinner bands of crystalline quartzite represent pure siliceous sediments. A number of the psammitic outcrops examined may represent metamorphosed granites. Rocks resulting from the metamorphism of argillaceous and calcareous sandstones are also present.

The main rock types included in this group are quartzites of varying purity, quartz, and quartz-feldspathic schists, granulites, and metamorphosed calcareous grits. Quartzites are commonly associated with metacalcareous rocks, but in general the psammites may occur interbanded with all types of basement metamorphics.

In some of the psammitic rocks garnet is developed, one sample being a garnet-biotite-quartz-feldspathic schist from Wādī Gharish Eastern Protectorate (A228). Shearing and fracture cleavage in these rocks is also recorded; the fracture cleavage is well developed in platy quartzite of the eastern Wādī Gharish area. Some psammitic rocks show well-developed feldspathization as noted in the following discussion.

Steeply dipping psammitic rocks form positive topographic features, and the purer forms of quartzite are, with crystalline limestone, the most resistant rocks of the region (fig. 7).

Specimen A120, from Wādī al Jahr, 15 miles west of Nūsh, is described as a banded garnetiferous muscovite psammitic and is one of the few rocks examined in which tourmaline occurs. In this specimen the mineral occurs commonly in crystals as much as 0.3 mm in length that show pleochroism from dark green to yellow brown. Some of the laminations in this rock are entirely quartzose; intervening layers consist of muscovite, twinned albite plagioclase, quartz, and potassium feldspar. Irregular muscovite flakes enclosing groundmass minerals are clearly porphyroblastic. The preservation of a recumbent microfold in one of the bands of this rock shows that all the bands represent pinched out micro-

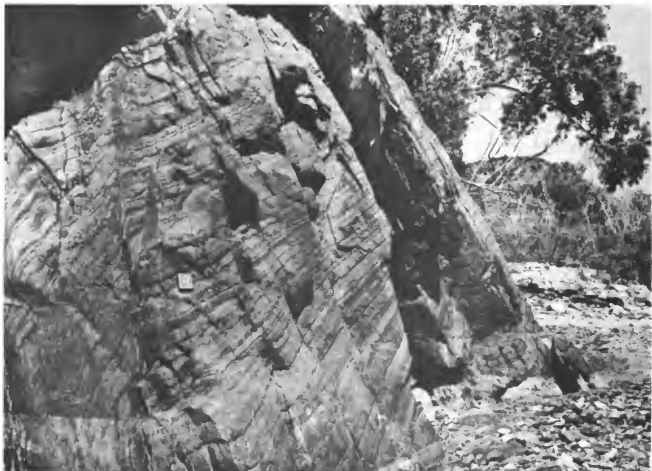


FIGURE 6.—Relic bedding in schist, Wādī Gharish. Matchbox shows scale.

folds and implies that the banding is of metamorphic origin. Polymetamorphism is indicated by the puckering of a previous schistosity.

On the south bank of Wādī Khawrah nearly opposite the town of this name occurs a banded epidote-quartz rock, or epidosite, in which an aggregate of quartz and granular epidote passes into a fine aggregate of quartz-epidote, oligoclase, and minor muscovite (A154). This rock is considered to represent a metamorphosed calcareous grit.

The metamorphism of an arkosic sediment is exemplified by deformed schistose quartzo-feldspathic rock exposed to the south of An Nuqūb in the Bayḥān area. The specimen (A186) shows microcline, orthoclase, and albitized plagioclase in a granular groundmass. Pale-green chlorite is plentiful; red-brown biotite and epidote are present in small quantity.

Between Niṣāb and Khawrah and to the southwest of Niṣāb are coarse-grained platy impure quartzites containing scattered flakes and discontinuous folia of biotite. Purer white quartzite is interbanded with

tremolite marble and biotite schist in the same area. The quartz appears to have recrystallized during metamorphism and is elongated parallel to the schistosity of adjoining rocks. In the range of hills some 6 miles northeast of Niṣāb, quartzite and quartz-garnet-biotite schist are interbanded with platy crystalline limestone. Quartzite and crystalline limestone occur interbanded in similar ridges on the margin of the Ramlat as Sab'atayn, some 13 miles north of Niṣāb.

Quartzites and quartz schists make up a considerable part of the northwestward-trending belt of metamorphic rocks between As Sufāl and 'Ataq. The quartzites include both massive dense blue-gray rocks and platy bedded types which are interbanded with chlorite and quartz-chlorite schists. In the northwest part of this belt, quartz schists are finely intercalated with chlorite schists, individual bands being only inches thick.

Granulites are represented in the belt of metamorphic rock that intersects the Jibāl an Nisfīn granite block. These granulites are derived from feldspathic sandstones and consist of an aggregate of quartz and feldspar,



FIGURE 7.—Rocks of the Aden Metamorphic Group, 3 miles west of Şa'id.

with biotite flakes and scattered crystals of garnet. In some types, devoid of garnet, muscovite occurs with the biotite. A rough schistosity is imparted to the muscovite and biotite by the micas. Biotite granulites also occur in Wādī Aḥwar.

Feldspathization of fine-grained quartzite has occurred in the Wādī Aḥwar area, as shown by the production of microcline and plagioclase porphyroblasts as much as 6 mm in diameter in a groundmass in which the average size is 1 mm or less. Feldspathization was also recorded in the area northeast of Nişāb.

METACALCAREOUS ROCKS

Metacalcareous rocks occur in most of the basement-rock areas visited, and even allowing for possible repetition by folding, their wide distribution indicates repeated calcareous depositional phases. The metacalcareous rocks are interbanded with other basement components and range in thickness from 6 to 180 feet or more. The rocks may occur in massive form, but in several areas they show a platy or laminated character. Rock types include marble or crystalline limestone, ophalcalcite, tremolite schist, and calcsilicate

rocks. A feature of note is the high proportion of magnesia-rich (dolomitic) limestone. In general, the metacalcareous rocks are highly resistant to weathering in the arid climate of the Protectorate and commonly form marked positive topographic features.

Thermal metamorphism of nonmagnesian slightly impure limestone is shown by an outcrop of banded idocrase-wollastonite marble adjoining the granite of Jabal al Mūmīf, Al 'Anad. A specimen of this rock (A18) shows 2-mm-thick bands of crystalline idocrase marble alternating with thinner bands of columnar wollastonite and idocrase. Much of the irregular idocrase is full of inclusions; some calcite occurs.

Thermal metamorphism of impure magnesian limestone is exemplified in ophalcalcite from Wādī Mīlī, some 12 miles southwest of Lawdar. The specimen (A81) shows serpentine pseudomorphs after forsterite set in euhedral dolomite. In the same area, ophalcalcite containing some chlorite is in contact with a pegmatite dike. The metamorphism of ophalcalcite and similar rocks is probably connected with the invasion of granite during the main syntectonic granite phase. In the

assemblage of pelitic and mafic schists and metacalcareous rocks of this area granitic bands are common.

Regional metamorphism, of calcareous sedimentary rocks resulted in a fine-grained tremolite schist at Wādī Raybān, southwest of Lawdar. In the same area is plagioclase-diopside-scapolite gneiss in which colorless euhedral diopside is surrounded by euhedral scapolite and unaltered oligoclase (A77). Birefringence indicates a lime-bearing scapolite. Small apatite crystals, common sphene, and sporadic garnet occur. The presence of disseminated pyrrhotite, which is the common sulfide mineral in higher grade regional metamorphism of calcareous rocks, confirms other evidence for metamorphism in the almandine-amphibolite facies. Petrographic study indicates that scapolite is in equilibrium with the feldspar in this rock.

A lower grade of metamorphism is indicated in epidote-quartz rock that forms a hill about 1½ miles northeast of Kawrah. This rock (A159) is composed of euhedral epidote in a granular fabric of quartz. It is thought to be derived from a calc-arenaceous sedimentary rock but might possibly represent an epidotized quartzite.

The wide distribution of metacalcareous rocks precludes description of all the observed outcrops, but some account of the more important of these is given below.

A traverse along Wādī Durā to the southwest of Niṣāb showed several bands of metacalcareous rocks in the basement assemblage of pelitic schists and quartzo-feldspathic schists and gneisses. A specimen from a 6-foot-thick band in quartz-biotite schist shows white to pink coarsely crystalline marble with sporadic flakes of muscovite and chlorite and a little quartz and feldspar. In the same area phlogopite-tremolite-dolomite marble, mainly consisting of crystalline dolomite, represents an altered impure magnesian limestone.

At As Sufal, east of Yashbum, dolomitic limestone is interbedded, in laminae ranging in thickness from ¼ inch to 6 inches, with quartz-chlorite schist (fig. 8). The overall width of the calcareous series is here about 30 feet but may reach 120 feet in the northwestern part of the same belt of metamorphic rocks. A specimen of the limestone shows patches of quartz and a little chlorite. The quartz shows strain effects, and evidence of shearing stress is seen in the rock.

The Jabal ath Thaniyah range in the Ramlat as Sab'atayn is composed largely of crystalline limestone, commonly dolomitic. The folded and generally steeply dipping limestone is associated with bands of amphibolite, hornblende-chlorite-epidote schist, and talcose schist. An east to west traverse over the northern part of the main ridge crossed an unaltered andesitic dike followed by a band of dolomitic marble which is



FIGURE 8.—Platy crystalline limestone interbedded with schist. Aden Metamorphic Group, As Sufal.

pink to white and about 170 feet thick. This band is followed by a band of gray marble some 6 feet thick, a specimen of which (A206) shows areas of granular quartz in a turbid mass of dolomite. To the west occurs a band of dark hornblende rock some 30 feet thick. This may be an amphibolite derived from gabbro, or may represent an altered calcareous shale. The metamorphic grade indicated is fairly high (almandine-amphibolite facies). In contact with this rock to the west is a band of white laminated crystalline limestone about 45 feet thick, in which the laminae are about 1 inch thick. This band is followed by blue laminated or platy crystalline limestone with intercalated brown and white limestone, about 180 feet thick. The traverse did not cross the whole ridge.

The thickness of metacalcareous rocks in the Jabal ath Thaniyah range is greater than seen elsewhere in the Protectorate, but these rocks are associated with metamorphic rocks comparable in grade and lithology with those in other outcrops of the Aden Metamorphic Group.

Crystalline limestone forms resistant bands in the granite of Mukayrās, Niṣāb, and Ṣa'īd. Extensive exposures of this limestone occur in the hill ridges 6 miles northwest of Niṣāb and in the Bayḥān area. Minor bands were seen in Wādī Aḥwar and in the metamorphic belt of the Jibāl an Nisīṭyn block. In Wādī Gharīsh, E.A.P., metamorphosed impure dolomitic limestone containing flakes of phlogopite and chlorite is present, and also metamorphosed calcareous sandstone.

METAMORPHOSED MAFIC IGNEOUS ROCKS

Metamorphosed mafic igneous rocks form a part of the basement assemblage in many of the areas visited. This section heading is apposite insofar as the bulk of the rocks examined are of mafic type, but some derivatives from intermediate igneous rocks are also included.

The main rock types include amphibolite and plagioclase amphibolite, hornblende-plagioclase gneiss (some diopside bearing), hornblende schist, and hornblende schist with chlorite and epidote, or epidote and actinolite. The feldspar in the samples ranges mostly between andesine and labradorite, but may include oligoclase and, in a few samples, albite. Some of the rocks are garnetiferous. Metamorphism reaching grades appropriate to that of the almandine-amphibolite facies is indicated. Migmatites composed of amphibolite impregnated and veined with granitic material occur in several areas, such as in Wādī Banā, and amphibolite bands in migmatitic gneiss are also seen.

The original rock types involved in metamorphism appear to have included gabbro and diorite although some altered dolerites are recognized. Some of the chloritic and actinolitic schists of both W.A.P. and E.A.P. represent altered volcanic rocks, but in places this cannot be confirmed. Hornblende pyroxenite of Wādī Gharish, E.A.P., is considered to represent an ultramafic intrusion. Evidence for the occurrence of ultramafic derivatives has not been obtained elsewhere in the region, a fact which suggests that their distribution is very limited.

In the area southeast of Kirsh, diopside-plagioclase gneiss occurs in basement rocks consisting mainly of mafic and semipelitic schists, which have been affected by later granite invasion with the production of migmatitic rocks. The gneiss consists of pale-green ferroan diopside associated with abundant green hornblende, which is in equilibrium with the diopside and does not replace it. Plagioclase, between andesine and labradorite in composition, is twinned but unzoned and shows slight saussuritization. Sphene is the only accessory. The rock has clearly been metamorphosed in the almandine-amphibolite facies and has an assemblage indicating an original mafic igneous rock—possibly a banded gabbro (specimen A36).

Additional rocks considered to represent metamorphosed gabbro crop out in the Jibāl al Aswad area where they form part of a belt of metamorphic rocks in a dominantly granitic province. A specimen of these rocks (A225) is a coarse-grained type in which some ferromagnesian minerals have been converted to pale-green actinolite associated with green biotite. Plagioclase has been albitized. The high lime and

alumina content indicated by the alteration products of the feldspar suggest original labradorite, whereas the large apatite crystals, altered ilmenite, and absence of quartz all suggest that the parent rock was a gabbro.

A metamorphic rock probably derived from a gabbroic or dioritic parent crops out north of Jī'ār in the Abyan district. This rock is a hornblende-plagioclase gneiss in which quartz and biotite are common. Feldspar is sericitized. Apatite, carbonate, granular epidote, and garnet occur in small quantities. Anhedral sphene is associated with the biotite.

Derivation from either a doleritic or gabbroic rock is indicated for a hornblende schist from Wādī Milh, southwest of Lawdar. The bulk of the rock consists of a fine mosaic of albitized plagioclase, with epidote green hornblende. The color index is high and quartz is a minor constituent.

Field examination of a number of mafic schists, which contain actinolite, chlorite, and epidote and in which inclusions of rock fragments were discerned, led to the conclusion that the schists represent altered volcanic rocks. Some confirmation is afforded by examination of a specimen of fine-grained epidote-actinolite-hornblende schist from the west of the main ridge of Jibāl ath Thantyah. In this specimen, epidote occurs in granular form, and also forms composite porphyroblasts around which schistosity is deflected. These porphyroblasts appear to be pseudomorphs of either phenocrysts or amygdaloids. Interstitial quartz is present, and some of the plagioclase may be of sodic type. Carbonate minerals occur in bands and plates. The rock may represent a metamorphosed andesite. Similar rocks are recognized in Wādī Rufād (north of Jil'ah), E.A.P., and in a locality some 6 miles north of Yashburn, where hornblende-chlorite-epidote schists are interbanded with psammitic rocks.

Conspicuous microcline and biotite in hornblende-plagioclase schist from Wādī Banā, to the northwest of Al Maṣānī, suggest potassic metasomatism associated with granitization. The high color index and mineral assemblage indicate an original mafic igneous rock. This schist forms part of a complex of mafic schists and gneiss and of pelitic schists, interbanded with felsic gneiss and cut by numerous feldspathic veins and dikes.

Polymetamorphism is indicated in porphyroblastic hornblende-chlorite-epidote schist from some 5 miles north of Yashburn. Hornblende in this rock appears to be breaking down under deformative stress.

In the upper reaches of Wādī Gharish, Eastern Protectorate, rock identified as hornblende pyroxenite (A232) is considered to represent an altered ultramafic intrusion. The dominant mineral in this unusual rock is a gray-green clinopyroxene—diopside or diopsidic augite—which occurs in crystals several millimeters

long and shows deformation effects. In places the pyroxene is enclosed in euhedral hornblende. Conspicuous feldspar consists of relic sodic plagioclase enclosed in perthitic microcline. Red-brown biotite occurs sporadically in bent laths. Sphene occurs in irregular crystals. Certain outcrops of this rock show very large pyroxene crystals and may be pegmatitic. Hydrothermal alteration has affected the rock to a variable extent; pyroxenes may be altered to amphibole and talc, and from these serpentine has been produced, so that specimens from the same intrusive body are described as serpentinite with conspicuous areas of proxene in antigorite(?). The serpentine shows deformation effects and carbonate veining. Apart from hydrothermal alteration, it is difficult to assess the degree of metamorphism this rock has undergone. It is possible that it was originally a peridotite, and in some of the serpentinous patches the outlines of olivine crystals can be seen. Under dynamothermal metamorphism the olivine may break down to tremolite (tremolitic hornblende) and talc, and at a high stage of metamorphism diopside may replace the amphibole. It is likely that the intrusion preceded the main stage of tectonism and regional metamorphism, and that the texture seen is of crystalloblastic type. The deformation shown may be attributed to a later period of dynamic metamorphism that affected a rock denuded of much of the superincumbent cover and thus at an effectively higher level in the crust.

GRANITIC ROCKS

Data from field, photogeological, and petrographical studies indicate that a number of phases of granitic invasion occurred in the Aden Protectorate. It is convenient to consider granitic rocks of various ages under one heading, and also logical, as they are considered to be genetically related in a granite series.

Before the granitic rocks are described, brief comment on the wider question of the origin of granite is pertinent, to provide a background to the interpretation offered and to clarify the meaning of the term "granitization" as used in the ensuing paragraphs.

Regarding the origin of various types of granite, the concept of zoning dependent on depth, and thus also dependent on temperature and pressure, is adhered to. This concept follows ideas advanced by Eskola (1933), by Read (1957), who stressed the factor of time as well as place, and by others. The weight of evidence appears to support the idea that granite emplacement involves movement of a partly liquid magma formed by differential fusion of mixed rock in the deep-seated basement assemblage. Such magma, which may be partly crystalline and perhaps more akin to mobilized migmatite, is squeezed upward by

earth movements to levels removed from the zone of fusion.

Whatever the ultimate origin of the granitic bodies exposed in the Protectorate may have been, it is clear that some have gradational contacts with surrounding rocks and that others are clearly crosscutting and have distinct thermal aureoles. In the first group, granitization by metasomatism is recognized insofar as this refers to an exchange of material between the main granitic body and the country rock. It is probable that the introduction of ions through aqueous and other fluids derived from crystallizing magma is here an important process. This type of granitization, with which sodium and potassium metasomatism and injection phenomena are associated, is likely to be most strongly developed where granitic material is emplaced at the height of tectonic activity, during periods of regional metamorphism. Activity is then stimulated by high temperature, pressure, and consequent mobility. The result of granitization is to produce rocks which, in respect to minerals or texture, are more like granite than they were before. The term "granitization," as here used, does not necessarily imply production of completely granitic rocks.

Peralkaline intrusive granite occurs in two localities, from one of which evidence for a Late Cretaceous to Tertiary age was obtained. These rocks are referred to as posttectonic alkaline granite.

The differentiation of granites of various types has not been possible in all areas and is the more difficult because granitic invasion of two or more periods may have occurred successively in the same general area. Field observations show that emplacements may be composite.

SYNTECTONIC GRANITE

Field reconnaissance and photogeological study indicate that syntectonic granite is areally the most extensive of the Protectorate granites.

Four main types of granite are recognized in the Aden Protectorate. The oldest, syntectonic granite, is associated with extensive granitization of surrounding rocks and with zones of migmatization (fig. 9), and is considered to have invaded rocks of the Aden Metamorphic Group broadly synchronously with the culmination of the main period of regional metamorphism, although certain phases of the invasion may have been prolonged beyond this time. The syntectonic granite does not appear to result entirely from the conversion in situ of existing rock, but rather to represent a partially mobilized magma-magma mix. The criteria by which this type of granite is recognized are given later in this report.



FIGURE 9.—Biotite schist and migmatite, 2 miles west of Şa'îd.

A second type of granite is designated "intertectonic." Granites of this class are nonfoliate intrusive rocks without the extensive zones of metasomatism that typify syntectonic granites. Their emplacement subsequent to the period of regional metamorphism which resulted in the Aden Metamorphic Group is shown by inclusions of metamorphic rock and older dioritic rock, but well-marked shearing and deformation effects indicate that they predated a phase of stress metamorphism.

A third type is represented by posttectonic calc-alkaline granites which show no deformation; some of these show discrete and sharp aureoles of contact metamorphism and they are commonly of relatively restricted outcrop area, roughly circular in plan. An early Paleozoic age is indicated by several age determinations.

Criteria by which syntectonic granites are recognized in the field, some of which are applicable in photogeological interpretation, include the following: Generally concordant and gradational relations with surrounding rock; no evidence that magma disturbed or displaced contact wallrock; absence of distinct thermal aureoles;

the presence of feldspar porphyroblasts and bands in country rock, which are larger and more abundant toward the main granite body and progressively diminish toward peripheral unaffected country rock; xenoliths in the granitic body are oriented parallel to the country rock; the peripheral parts of a large granite mass are commonly gneissose and may show flow effects, and augen and flaser textures may be developed; the foliation of granitized country rock is parallel to that of invasive gneissose granite.

Criteria recognizable in petrographic examination include the following: Variety in size and form of mineral grains; presence of abnormally large crystals such as feldspar porphyroblasts; clear crystals in a mainly turbid rock; extensive albitization and abundant myrmekite and myrmekitic intergrowth; presence of much epidote; pseudobrecciate structure.

Many of the features noted above indicate granitization; others result from the emplacement of granitic material synchronously with stress accompanying regional metamorphism. The field examination of a number of syntectonic granites leads to the suggestion that these are partly of subautochthonous type and partly transitional between subautochthonous and cross cutting granite. Thus they show feldspathized peripheral areas and migmatitic and gneissic zones, as well as homogeneous magmatic areas.

Features typical of the syntectonic granite of the Protectorate were illustrated in a traverse southeastward along the newly made track from Al Kirsh to Lahj, which runs to the west of and parallel to the upper Wādī al Kayfi. The progressive alteration of country rock about a central granite area is demonstrated over a distance of about 5 miles (figs. 10, 11). At the northern end of the traverse pelitic and mafic schists are sparsely invaded by thin bands of granitic material, accompanied by thin feldspathic bands and stringers. About 4 miles from the central granite is a belt of migmatite consisting of coarse-grained granitic material injected into hornblende schist. This is succeeded by hornblende-plagioclase gneiss cut by bands of feldspathic and granitic material some 6 inches thick oriented parallel to the foliation of the gneiss. The feldspathic bands are pygmatically folded. There follows a zone of biotite schist with profuse feldspar porphyroblasts, in which are bands of gneissose granite some inches thick. A more extensive zone of migmatite precedes foliated granite containing elongate patches of schist, which are feldspathized and cut by numerous feldspar bands. The schist shows diffuse borders; it also occurs as impersistent thin streaks in the granite. The central granite is of calc-alkaline type and shows shearing and granulation. The strike of foliation planes in less altered country rock, migmatite, and

foliated granite is uniform at about N. 70° E. In this area, as elsewhere, dikes of feldspar-quartz-mica pegmatites are associated with the granite. Such dikes appear to be much restricted in areas of later granites.

A further demonstration of the characteristics of syntectonic granitic invasion, accompanied by granitization, was afforded by a traverse along an unnamed north-south trending wadi which reaches the coast some 10 miles west of 'Irqah. Here is shown a gradational passage from central nonfoliate biotite granite, through peripheral zones of gneissic biotite granite with feldspar augen reaching 2-inch diameter, into an outer zone where foliated granite is banded with biotite and muscovite schist. Patches of migmatitic rock occur. Bands of gneissose granite continue to appear in the metamorphic country rock for several miles from the focal point of granitic invasion. For a distance of some 6 miles from the central granite, feldspathization of varying intensity affects surrounding rocks, which include pelitic, mafic, and psammitic schists. In the more central zone are feldspathic bands and stringers; these give way outward to lenses and patches of feldspar, and finally to feldspar porphyroblasts in schistose rock. The feldspar bands generally are oriented parallel to schistosity planes of the country rock and are contorted and pygmatically folded concordantly with the country rock, conditions indicating invasion synchronously with regional metamorphism when all rocks were plastically mobilized. Pegmatitic bodies, dikes, and lenses are abundant in the central zone and in several places consist almost entirely of

muscovite. Pink garnet occurs in the feldspar of many of these pegmatites. Quartz veins and stringers are associated with pegmatites but, unlike these, also occur in peripheral metamorphic rocks.

The history of granite formation in this area is interpreted as a migma-magna invasion toward the end of a major period of regional metamorphism, the mobilized material being displaced upward above the zone of origin, but at a relatively low level. Metamorphosed sedimentary rocks were partly granitized. Close to the focal point of the invasion some migmatization of country rock occurred. Bands of crystalline limestone in the area remained unaffected by granitization. In the waning phases of granitic invasion, pegmatites were injected in the central zone while quartz veins formed in zones more remote from the focal point of invasion.

Foliated syntectonic granite occurs in Wādī Banā a few miles northwest of Al Maṣānī'. The rock crops out mainly in bands some 3 feet thick in an assemblage of pelitic schists and hornblende-plagioclase gneiss. Feldspathization is well marked in this area in the form of porphyroblasts in the schists, and numerous feldspathic lenses and bands, some of which reach a thickness of 30 feet. Quartz veins are few and small. A specimen of foliated granite from this locality (A62) is a quartz-feldspathic-biotite gneiss of granitic composition, in which porphyroblasts of pink orthoclase up to 1 cm long commonly contain relic patches of microcline. Quartz shows strain effects. Myrmekite is fairly conspicuous. From laboratory study it is not possible to determine whether the rock represents a deformed and recrystallized granite or a granitized sedimentary rock.



FIGURE 10.—Feldspathized biotite schist, 5 miles southeast of Al Kīrah.



FIGURE 11.—Hornblende schist impregnated with granitic material, Wādī al Kayfīl.

However, large potassium feldspars, dark quartz, and a pseudobrecciated appearance indicate the latter, and this is supported by field observations.

A traverse along Wādī Raybān and Wādī Mīlḥ to Al Mājīl, 8 miles southwest of Lawdar, showed invasion of syntectonic granite into metamorphic rocks that were mainly hornblende-plagioclase gneiss and pelitic schist, with metacalcareous and quartzitic representatives. The foliated granite occurs as numerous bands some of which are as thin as 6 inches. Intense epidotization affects adjoining rocks. Feldspathic bands and stringers are numerous; some grade into granitic rock. Quartzites show abundant porphyroblasts of white feldspar. Pegmatites are well developed and some contain garnet. A notable pegmatite dike some 210 feet thick extends more than 1½ miles along Wādī Mīlḥ; its emplacement seems to be related to faults along the wadi. A specimen of gneissic granite from this area (A71) shows several features indicative of granitization. These include a pseudobrecciated appearance (large areas of quartz or microcline surrounded by smaller areas of the same material showing no apparent granulation); abundant myrmekite; conspicuous microcline porphyroblasts; and erratic variation in grain size.

Protoclastic effects are recognized in certain granitic rocks of this area; the rocks are considered to have been partly crystallized and to have contained diminished interstitial liquid, which flowed under differential stress. The crystals were ground together and deformed. Evidence of granulation is accompanied by relics of larger crystals.

The granite of the Mūdiyah area is largely of post-tectonic type; but on the eastern flank of this intrusive granite is foliated granite in bands some 6 feet thick, alternating with hornblende and biotite schists and associated with feldspathic bands. In some localities plugs of later red intrusive granite appear to cut this syntectonic granite.

Farther to the east of Mūdiyah, in the Nūṣah locality, the effects of syntectonic invasion are shown by the occurrence of biotite schists heavily studded with feldspar porphyroblasts. Some 3 miles northeast of Nūṣah, migmatites have resulted from the injection of granitic material into hornblende schists. Mafic components show marginal enrichment in biotite and are finer grained toward the granitic layers.

Traverses from the central part of the granite in the Ṣa'īd area outward to the eastern, western, and northeastern borders indicate that this is a composite body of later intrusive granite emplaced in older syntectonic rock. The intrusive rock is homogeneous, nonfoliated, and intensely jointed. The peripheral syntectonic granite is foliated and crops out as bands in feldspathized and granitized country rock; further-

more, this granitic rock is associated with numerous pegmatite dikes which are apparently absent from the central granite. Aerial photographs show a distinctive contrast in weathering habit between resistant peripheral syntectonic granite and the much reduced intrusive type.

At Nīṣāb, as in the Ṣa'īd area, there appear to be two types of granitic rock, namely a foliated syntectonic granite which is generally peripheral to a nonfoliated intrusive variety of later date. About 12 miles south of Nīṣāb, syntectonic granite forms a gradational contact with schistose country rock. The bedded character of the granite, which is clearly seen on aerial photographs (fig. 12), may be due to relic bedding expressed by differential weathering; if so, it supports the view that much of this foliated rock results from granitization. A specimen of garnetiferous granite gneiss from the south of Nīṣāb (A147) consists mainly of orthoclase, sodic oligoclase, quartz, brown biotite, and green amphibole. The high feldspar content and the general appearance of the rock indicate a syntectonic type.

Granite of the Jībāl an Nīsiyīn block, the center of which lies some 30 miles northwest of Nīṣāb, is mainly of nonfoliated later intrusive type; but at Al Ḥuṣfān to the southeast of the block and at Wādī Maṭarīl on the northeast border, gneissic biotite granite with feldspar augen is exposed. This is interbanded with biotite-chlorite schists and metacalcareous rocks. The main granite block is intersected by a northwest-trending belt of metamorphic rocks in which some quartz-feldspathic gneisses appear to have been formed by granitization. Foliated granitic rocks of this belt show gradational contacts with feldspathized schist or are in contact with quartzitic rocks resistant to granitizing processes. Specimen A181, from the northwestern end of the metamorphic belt, is quartz-feldspathic gneiss showing pronounced biotitic banding. Altered microcline occurs in phenocrysts as much as 1 cm in diameter, and also interstitially. Calcic oligoclase may also occur as phenocrysts showing deformation. Myrmekite is common, and granular epidote is present as an accessory mineral. Petrographic study suggests that the rock represents a granitized metasedimentary rock which suffered subsequent deformation. The alternative possibility of a deformed adamellite is considered less likely.

In the Jībāl al Aswad range, flanking the plain to the north-northeast of Mayfa'ah (Al Wāḥidī), granitic rocks are bordered to the north by a belt of metamorphic rocks. The eastern part of this range was not visited, but aerial photographs show an apparently sharp contact between homogeneous granite and metamorphic rocks.



FIGURE 12. Syntectonic granite, 15 miles south of Nişāb. Foliate granite (1) shows a "bedded" appearance indicating selective and incomplete granitization. To the south of the grant area, pelitic and mafic schists are seen (2). Volcanic vents and basalt flows of the Aden Volcanic Series occur (3). Royal Air Force photograph. Crown copyright reserved.

In the western part of the range, granitic rocks form a gradational contact with metamorphic rocks, and zones of mixed or granitized rocks are present. A traverse across the granitic area into metamorphic rocks revealed a degree of feldspathization unexcelled in any other area visited. Foliated biotite granite grades into coarse feldspar-quartz rock in which a faint foliation is defined by sparse laminae of biotite. Feldspar crystals in this rock may reach $2\frac{1}{2}$ inches in diameter. As inclusions within the granite and interbanded with it are quartz-biotite-chlorite schists and biotite schists, thickly studded with feldspar porphyroblasts for several inches from the granite margin (figs. 13, 14) and showing lesser concentrations of these porphyroblasts form many yards from the junction zones. Impersistent quartz veining was noted, but pegmatites were not seen. The dominant feature of this area is feldspathization. This, with other field observations, indicates invasion of chemically mobile granitic material under favorable conditions for metasomatism such as would obtain were granitic invasion contemporaneous with regional metamorphism. It seems that the western part of the Aswad range is largely syntectonic granite, whereas in the east the granite is probably a later intrusive type.

Syntectonic granite, associated with zones of feldspathization and commonly with migmatitic areas, was also observed near 'Awābil; near Tor al Baha; in Wādī Aḥwar; in the Al Khabr area; south of Khawrah; and in the Bayḥān area. In the Bayḥān area, granite representative of the syntectonic phase appears to be restricted in occurrence, and here also the presence of granites of intertectonic and posttectonic periods, together with paragneiss, makes separation particularly complicated.

In summary, focal points of syntectonic granite invasion are recognized in many areas of the Western Protectorate. Invasive material seems to have been partly of magmatic character, and partly of a composite magma-magma type; it is represented by granites of calc-alkaline composition, and less commonly by adamellites. These are foliated rocks, at least in the zones peripheral to foci of invasion. The granitic rocks are associated with extensive zones of feldspathization in many places with migmatitic areas of rather limited extent. In a number of places the metamorphic grade of surrounding rocks is affected for several miles from the granite center. Pegmatites occur as a characteristic feature, and in these muscovite (as books) and garnet-bearing feldspars are well developed. No pneumatolytic deposits, typically connected with many intrusive granites, have been recorded. Evidence for granitization rests mainly on general field relations, but is supported by some petro-



FIGURE 13.—Feldspar porphyroblasts in biotite-chlorite schist, Jibāl al Aswad area.



FIGURE 14.—Feldspar porphyroblasts and thin quartz veins in biotite schist, west-central Jibāl al Aswad range.

graphical study. Several specimens examined show proclastic effects pointing to invasion during crustal stress. Recrystallization noted in several specimens indicates phases of renewal of stress within the main episode of regional metamorphism. Deformation of cataclastic type is attributed to a later period of mainly dynamic metamorphism.

INTERTECTONIC GRANITE

Rocks assigned to the intertectonic class are non-foliate granites without extensive zones of metasomatism or migmatization. They are further distinguished from syntectonic granites by the absence or very restricted development of associated pegmatites.

The later origin of intertectonic granites is indicated by the fact that in the Mukayrās area these show inclusions of dioritic rock which is clearly differentiated, by the absence of any considerable degree of regional metamorphism, from the mafic components of the Aden Metamorphic Group. Evidence that syntectonic granite invasion was roughly coeval with metamorphism of this group has been noted. It is therefore considered that the dioritic rock and associated intertectonic granite postdated syntectonic granite. The intertectonic granites are characterized by cataclastic effects, deformation, and shearing, which indicate emplacement prior to a period of dynamic metamorphism; by this they are distinguished from posttectonic granites.

Rocks of this group include calc-alkaline hornblende and biotite granites, granodiorites, and syenites. They are exposed in the Mukayrās-Khawrah region, and possibly also near Jabal ath Thanyah in the Ramlat as Sab'atayn.

Granite exposed in the Mukayrās area is typically a nonfoliate pink feldspar-hornblende-bearing rock, in which the amount of biotite is variable but generally small. Epidote is common as patches and bands in the granite, and it lines shear planes. The granite is well jointed. A specimen from 3 miles northeast of Mukayrās shows calc-alkaline granite with large phenocrysts of perthite and sodic plagioclase in a groundmass of albite, oligoclase, quartz, fawn-colored biotite, and hornblende. Plagioclase is partly epidotized. In the same general area occurs hornblende adamellite in which quartz plates are full of shatter cracks. Traverses southward from the central area of the granite in the Mukayrās area suggest a zoning from hornblende granite through granodiorite and quartz diorite to hornblende diorite. The impression gained in the field was that the center of the granite is more biotitic than hornblende.

The relation of the granitic rock to dioritic intrusives suggest that the latter predated the granite by a short interval, and contamination by interaction with this earlier more mafic rock resulted in hybridization. Evidence of hybridization is seen in a specimen (A105) from some 5 miles northeast of Mukayrās. This is a hornblende microgranite containing perthitic phenocrysts and prisms of green hornblende, many of which are zoned, with a core of blue-green amphibole surrounded by darker hornblende. Darker patches in the rock contain more abundant amphibole, and in these

perthite is absent. In a specimen (A110) from 'Aryab, 2½ miles east of Mukayrās, calc-alkaline granite passes gradually into a quartz diorite.

In the Khawrah district, nonfoliate hornblende granite contains inclusions of dioritic rock of the same type as seen at Mukayrās, and also contains inclusions of older mafic metamorphic rock. A noteworthy feature of the Khawrah district is the presence of a number of reduced arenalike areas of subcircular shape. These were first noted on aerial photographs. One of the arenas, about 11 miles south-southwest of Khawrah, was visited, and it proved to consist of syenite surrounded by more resistant dioritic rocks. The diameter of this arena is about 1½ miles. The outer surrounding rocks are mainly hornblende-plagioclase gneisses which pass inward to nongneissous quartz diorite and diorite, into which the syenite was intruded. It seems probable that the nonfoliate diorite was also intruded through the older gneisses and is equivalent to the diorite of Mukayrās.

Altered granitic rocks from isolated small hills some 4 miles west-southwest of the northern ridge of Jabal ath Thanyah may perhaps represent intertectonic rocks. Specimens show granodioritic types in which quartz shows strain effects. Bent actinolite laths show a parallel arrangement that suggests incipient schistosity.

POSTTECTONIC GRANITE

Granites of the posttectonic class occur typically in fairly restricted outcrops, generally subcircular in plan, and they display evident crosscutting relations with surrounding rocks. Contact zones of thermal metamorphism are narrow and distinct. Lineation, if present, is such as may arise as a primary flow structure during consolidation of a magma. In some places, as at Nişāb and 12 miles southeast of Bayḥān, distortion of basement-rock strike due to intrusion of granite is seen. Posttectonic granites show strong, commonly intense, jointing. Their weathering characteristics contrast with syntectonic granite and associated granitized rock, which in several districts, such as in the Şa'id area, form upstanding margins to the much reduced later intrusive rock. Some of these features can be recognized on aerial photographs, but because these granites in certain areas have been emplaced in older granite, some of the characteristics noted may be lacking.

Most of the posttectonic granites are of calc-alkaline type. Determinations made for a number of these indicate an apparently early Paleozoic age. Alkaline granites of much restricted occurrence are probably of Tertiary age.

CALC-ALKALINE GRANITE

In the Lawdar-Mūdiyyah district occur two varieties of posttectonic granite—a medium-grained gray rock and a finer grained red granite whose coloration is due to altered iron-bearing and limonitic stringers. These rocks consist of microcline, oligoclase, and quartz, accompanied by biotite and muscovite. In the granite 4 miles northeast of Lawdar, inclusions of biotite schist and bornblende schist reach areal dimensions of 90 by 30 feet and show sharp contact with enclosing granite. Pegmatites are sparsely distributed and of small extent. Quartz veins are numerous and appear to be characteristic of posttectonic granite. Weathering to exfoliated domes and kopjes and concentric (onion-skin) weathering of boulders is well marked; this also seems to be typical of later intrusive granites (fig. 15).

Granite similar in composition and texture to the granite in the Mūdiyyah district underlies the sandy plain of Jawl as Salab to the southeast of Nişāb and constitutes most of the Jibāl an Nisīym block northwest of Nişāb.

In the Baybān area, notably to the south and northwest of the town, aerial photographs show a number of subcircular depressed areas of light tone and without lineations, surrounded by topographically higher metamorphic rocks. By analogy with similar features visited in the field, these are thought to be intrusions of posttectonic granite. They are clearly distinguishable from granitized rock, which shows a foliation parallel with adjoining metamorphic rocks.

Some 10 miles northeast of Baybān, in the Wādī al Jif'iyah area, is a granite containing conspicuous biotite, microcline perthite, and oligoclase (A201). The relations with adjoining schist suggest intrusion. The rock

shows a faint lineation due to parallel orientation of biotite flakes, but is not gneissose. Age determinations indicate an apparent age of 552 m.y. (million years). In the same general area gneissic syntectonic granite is recognized, into which the dated granite appears to be intrusive.

A clear example of posttectonic granite is seen in the Burūm area of E.A.P., where a medium-grained gray granite is cut by dikes or bands of finer grained red granite. Interlacing quartz veins are more commonly associated with the later red fraction. Inclusions in the granite consist mainly of altered hornblende rock. A specimen of this well-jointed granite (A257) shows large areas of microcline perthite, zoned plagioclase, and quartz. Partly chloritized fawn-colored biotite is conspicuous. Accessory minerals include sphene, zircon, apatite, and iron oxide minerals. To the south and east the granite is in contact with older volcanic rocks of mainly andesitic type (fig. 16). The contact is sharp, and where examined a thermal aureole about 12 to 18 inches wide is developed, the contact rock being an andesitic bornfels with porphyroblastic hornblende. For about 100 yards from the contact leucocratic granite and microgranite dikes cut the volcanic rocks. The dikes are about 3–6 inches wide. Age determination on biotite from this granite gives an apparent age of 515 m.y.

At Jabal Zūlm ash Shaybah, about 2½ miles northwest of Ra's Huṣayṣah, E.A.P., a granitic cupola intrudes older volcanic rocks, with the production of a hornfelsed contact zone. In Wādī al Ghabar, E.A.P., some 3 miles northwest of Mudbanīyah-Al Ghabar wadi junction, granite also intrudes older volcanic rocks. In this outcrop, as at Mūdiyyah and Burūm, a finer grained red feldspar variety is associated with a coarser gray variety. No deformation effects have been noted in thin section (specimen A249). Dating of this rock gives an apparent age of 652 m.y.

Apart from those just mentioned, posttectonic granites of calc-alkaline type occur at Ṣa'id (previously noted in connection with syntectonic granite) and in Wādī al Kayfī, 11 miles south-southwest of Al Musaymir. The Wādī al Kayfī rock provides a further example of later granite apparently intrusive into earlier syntectonic granite. A specimen of the Wādī al Kayfī granite gives an apparent age of 480 m.y.

ALKALINE GRANITE

Specimens proving to be alkaline granite were obtained from the northern part of the granite at Jabal al Munīf in the Al 'Anad area. It is not known whether all the granite near Jabal al Munīf is of alkaline type; variations in composition and texture observed in the field suggest that some may not be. Calc-alkaline granite is



FIGURE 15.—Intrusive granite, 6 miles south-southwest of Nişāb.

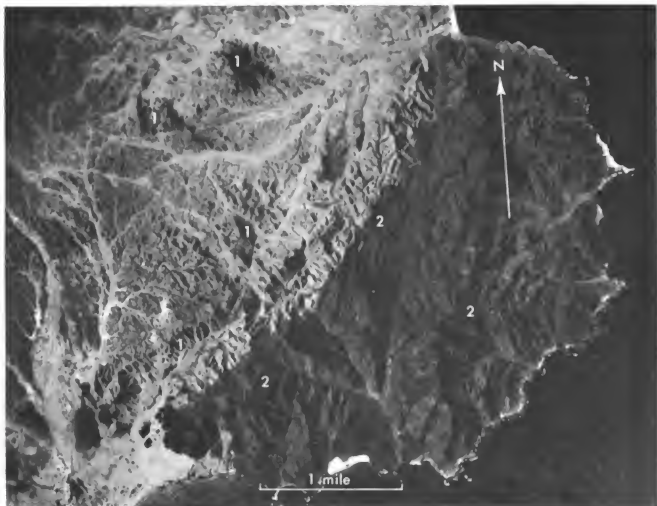


FIGURE 10.—Intrusive granite of Ra's Burūm, E.A.P. The sharp contact between the posttectonic granite (1) and older volcanic rock (2) is clearly shown. Royal Air Force photograph. Crown copyright reserved.

known to occur 2 miles northwest of the site of the alkaline granite specimen. The latter (A17) contains aegirine, zoned and margined by aemite, and sodic amphibole showing intense pleochroism from deep blue green to greenish yellow. Feldspar consists of albitized plagioclase partly replaced by potassium feldspar, together with large areas of perthitic potassium feldspar, also altered. Quartz is abundant. From the same area, alkali-microgranite with sodic amphibole was obtained.

Alkaline granite also occurs about 2 miles north-northeast of Mukayrās. A specimen of this (A101) shows riebeckite in a single-feldspar (perthitic orthoclase) rock. The extent of this alkali granite—in an area of predominantly calc-alkaline type—was not established. It is likely to be small.

The alkaline granite of Jabal al Munif shows relations with Cretaceous sedimentary and volcanic rocks of the Aden Trap Series which strongly suggest intrusion

through these rocks. It is considered that part, if not all, of the Jabal al Munif granite mass was erupted later than contiguous basaltic lavas, and is probably of later Tertiary age. It is tempting to opine that the only other representative of alkaline granite recorded in the Protectorate, near Mukayrās, is of the same age. There is no field evidence to support this assumption. However, on the evidence from Jabal al Munif and on general considerations of petrogenesis, both the alkaline granites are tentatively regarded as younger than the calc-alkaline posttectonic granites.

It is of interest that Geukens (1960) described intrusive Tertiary granites in Yemen; and Karrenberg (1959) mentioned alkalic and transitional types in Yemen, which he also dated as Tertiary.

The alkaline granite may possibly be the product of differentiation of basaltic magma, as these small and conceivably shallow bodies at Jabal al Munif, as in

Yemen, are associated with volcanic rocks that comprise a large proportion of mafic lavas. These latest granites may thus be of different origin from the majority of Aden granites.

MAFIC INTRUSIVES INTERTECTONIC MAFIC INTRUSIONS

A group of intermediate to mafic rocks show a moderate degree of metamorphism, mainly of dynamic type, resulting in shearing, deformation, and cataclastic effects. Their metamorphic state is not compatible with their having undergone the regional metamorphism responsible for the conversion of intrusive mafic igneous rocks to reconstituted gneisses and schists of the Aden Metamorphic Group. Thus they are considered to have been emplaced between the main period of regional metamorphism and a later period of dynamic metamorphism which also affected rocks of Wādī al Ghabar, E.A.P., regarded as latest Precambrian in age. The intertectonic mafic intrusives are generally nonfoliate rocks. They appear to have predated, by a short interval, the intertectonic granites; and by interaction with the latter, contamination and hybridization resulted. This is mentioned in the section "Intertectonic granite."

Rocks of this group are recognized mainly in an area approximately bounded to the east by a line from a point 5 miles west of Niṣāb extending southwestward along Wādī Durā and continuing with some south-eastward displacement along the escarpment of the Kawr al 'Awādhil to the locality of Mukayrās. To the west, the Yemen boundary limits observed exposures. This area includes the towns of Mukayrās and Khawrah. Intertectonic rocks are here associated with metamorphic rocks of the Aden Metamorphic Group, and in the Khawrah district, with limited exposures of syntectonic granite.

More limited occurrences of these rocks were recognized in the Wādī al Jif'iyah area, 12 miles northeast of Bayḥan, and in Wādī Milḥ, 14 miles southwest of Lawdar.

The rocks are mainly of dioritic and gabbroic type; quartz diorite, or tonalite, is also recorded.

The relation of intertectonic rocks to older rocks of the Aden Metamorphic Group is illustrated in a number of exposures in the Mukayrās pass. Rocks exposed on the Mukayrās plateau consist of dioritic and granitic plutonic intrusives cut by numerous dikes; toward the southern edge of the plateau dioritic rocks contain inclusions of hornblende schist. About 1½ miles north of the pass head is a belt of hornblende-plagioclase gneiss interbedded with hornblende schist, and at the top of the pass these metamorphic rocks are intruded by nonfoliate dioritic rock containing inclusions of the

older rocks; further descent of the pass proved alternations of intrusive and metamorphic rock, the proportion of the latter increasing toward Thirah at the foot of the pass. The rocks are much fractured, and shear zones are common. Epidote is abundant, as streaks and patches, in rocks of all types. Dikes of andesite-basalt in this area contain inclusions of the intrusive dioritic rock. The Mukayrās pass section confirms the conclusion that dioritic (and granitic) rocks of the Mukayrās plateau belong to an intrusive phase post dating the main regional metamorphic episode.

A specimen (A98) from the Mukayrās pass at an altitude of 5,300 feet is a slightly metamorphosed medium-grained diorite, in which turbid oligoclase is the dominant feldspar. Prisms of amphibole occur, together with more abundant actinolite. The rock shows an epidote vein 1 mm thick. Shear lines and schistose areas are conspicuous in thin section. Dark fine-grained inclusions may be recrystallized basalt or gabbro, possibly representing included mafic rock of the Aden Metamorphic Group.

A specimen of altered quartz diorite, or tonalite (A114), from the top of the Mukayrās pass, contains quartz which invariably shows strain effects; allanite is broken by deformation, and shear lines are present.

A rock (A97) consisting of epidote and albite, the latter in turbid deformed crystals, occurs in the pass in a zone of intense shearing and epidotization. This rock could have been derived from metamorphism of an anorthosite, and as the alteration shown is more intense, it may possibly be a representative of an older metamorphic rock.

The Khawrah area consists largely of hornblende rocks, in which hornblende-plagioclase gneiss and hornblende schist are associated with nongneissose dioritic rock containing inclusions of the metamorphic rocks. Field relations suggest that nongneissose dioritic rock is of later intrusive type. It was not established what proportion, if any, of the gneissose diorite represents the result of dynamic metamorphism upon later intrusive diorite. Certain altered dioritic rocks in this locality (for example, A151, from 2 miles southeast of Khawrah), which contain apparently recrystallized quartz together with amphibole after pyroxene, may be derived by metamorphism of older gabbro accompanied by granitization. Other slightly altered dioritic rocks showing marked deformation are more certainly of the intertectonic group.

In the Wādī al Jif'iyah (Bayḥan) district a restricted outcrop of mafic intrusive rock occurs in a predominantly granitic area. A specimen of this unusual rock (A264) consists almost entirely of bytownite and hornblende. The rock has clearly been subjected to some deformation, which has had little effect on the feldspar.

Deformation cracks are marked by lines of finely granular hornblende and recrystallized feldspar. The rock is designated a deformed hornblende-gabbro.

Amphibole-plagioclase rock in Wādī Mill, which has undergone a moderate degree of metamorphism, is thought to belong to the intertectonic intrusive group. Deformed amphibole crystals show cataclastic effects. Mineralogy and texture suggest derivation from a unalitized and albitized gabbro.

LATER MAFIC INTRUSIONS

Intrusions of mafic rock which appear to have undergone little or no metamorphism, were seen in two areas of the Western Protectorate. These are considered to represent a probably limited phase of intrusion later than the dynamic metamorphism which affected the intertectonic mafic intrusives and earlier rocks. Their unmetamorphosed state suggests an age later than Precambrian, and possibly early Paleozoic.

On the west of the 'Ataq road, about 6 miles south of 'Ataq, are dark cone-shaped hills of gabbroic rock. Petrographic examination proved unalitized gabbro, which has a grain size of about 1 mm and in which fresh unzoned labradorite is present. No deformation effects were noted in this rock (A136). A mile or so nearer 'Ataq, more outcrops of this rock are flanked to the east by chloritic schists and metacalcareous rocks.

Partly unalitized leucogabbro occurs at Jabal al Munif, Al 'Anad. A specimen (A31) shows labradorite enclosed optically in colorless pyroxene which is partly converted to pale-brown hornblende.

In order to include all basement-rock units of the Protectorate, two further groups, which occur only in E.A.P., must be considered.

OLDER VOLCANIC ROCKS

A series of volcanic rocks crops out over extensive areas in the E.A.P., notably in the Zulm Bā Tha'lab locality, some 19 miles north-northeast of Bi'r 'Alī; in various areas along the coast and inland between Ra's ar Rujaymah and Burām, and in Al Mukallā area. Beydoun (1961) described these rocks and named them the Tha'lab Group.

In summary, they comprise a thick series of volcanic rocks including olivine basalt, porphyritic pyroxene and hornblende andesite, keratophyres, and soda rhyolites; trachytes are scarce. Associated with the lavas are pyroclastic rocks, ranging from fine ash to coarse tuffs of lithic, vitric, and crystal type. The volcanics are predominantly of andesitic composition.

Rocks of this group were examined in several localities during the O.G.S. field survey. Specimens collected included altered volcanic tuff (A269), albitized olivine-andesite (A239), and various porphyritic types. Serpentinization and epidotization are common features,

and amygdalae infilled with epidote occur in many of the lavas.

The older volcanic rocks have undergone intense multidirectional cleavage and fracturing; although in one locality, about 1 mile north of Ra's Muwaysah, schistose hornblende-chlorite rocks occur, these rocks in general show the effects of dynamic rather than dynamothermal metamorphism.

In Wādī Gharish, north of the port of Balhāf, metamorphic rocks, including staurolite-garnet-mica schist, and schists showing polymetamorphism, occur some 15 miles from Zulm Bā Tha'lab, where older volcanic rock were examined. The older volcanic rocks probably also occur very much nearer to Wādī Gharish, as suggested from photogeological mapping. To the southeast of Ma'bar, Wādī Hajr, quartzzo-feldspathic gneisses are contiguous to older volcanic rocks. It is considered unlikely that the volcanic rocks cropping out so near to regionally metamorphosed rocks could have been exposed to the metamorphism which affected the latter and yet remain so little altered. In this connection it is noted that volcanic derivatives in basement rocks (Aden Metamorphic Group) of Wādī Gharish and of W.A.P., are reconstituted schistose rocks. It is suggested that the older volcanic rocks were extruded later than the main period of regional metamorphism which produced the Aden Metamorphic Group.

On the evidence of cleavage and intense fracturing, the volcanic rocks predate a phase of dynamic metamorphism. This metamorphism affected metasedimentary rocks of Wādī al Ghabar which, on the basis of contained conglomerates with volcanic fragments, are younger than the volcanic rocks and are thought to be of latest Precambrian age. The age of the older volcanic rocks might thus be somewhere between the date of the main regional metamorphism and a phase of dynamic metamorphism, possibly in late Precambrian times.

It is suggested that the older volcanic rocks of E.A.P. may be broadly coeval with the intertectonic intermediate to mafic plutonic intrusives of W.A.P., which also appear to be later than the main regional metamorphism but which have suffered deformation and cataclasis. The question is then raised as to the conditions which resulted in extrusive activity in E.A.P. concurrently with plutonic intrusion in W.A.P. In this regard it is noted that the lightly metamorphosed sedimentary rocks of E.A.P. are not recorded in W.A.P. That these younger metasedimentary rocks have been denuded from western areas, in what was a more elevated part of the shield, and with them the equivalents of E.A.P. extrusives seems a reasonable postulation.

It should be noted that Beydoun (1961) regarded the

volcanic rocks as the oldest exposed rocks in southwestern Hadhramut. Although the view just advanced is preferred, conclusions must be regarded as tentative.

GHABAR GROUP

Weakly metamorphosed sedimentary rocks exposed in the Wādī al Ghabar area of E. A. P. have been described by Beydoun (1960, 1961); he named them the Ghabar Group, in which he also included rocks in limited exposures in Wādī Minhāmīr (Wādī Ḥajr basin, near Ma'bar) and in Wādī Bā'Arayāt.

Rocks of Wādī al Ghabar were examined during the O.G.S. survey. In summary, the succession includes the following, described in ascending order:

At or near the base is a purple conglomerate containing pebbles and fragments of tuff, andesitic volcanic rock, chert, porphyry, crystalline limestone, and quartzitic rock. (Pebbles of pyroxenite, diorite, dolomite, siltstone, mudstone, and rare granite were also recorded by Beydoun, 1961.) The sedimentary succession is considered to lie unconformably upon older volcanic rocks, and volcanic pebbles contained in the conglomerate appear to be identical with rocks of this group exposed nearby.

Above the conglomerate are platy thin-bedded limestones containing some gypsum, and chert layers overlie the bedding. These are succeeded by a series of dolomitic rocks, calcareous sandstones, and siltstones with interbedded dolomite and gypsum layers. Overlying these are sandy dolomites, massive calcareous quartzites, thinly laminated shaly rocks of phyllitic character alternating with quartzites, and limestones.

No fossils have been recorded in these beds, and shale samples tested palynologically were devoid of fossil spores.

The rocks of Wādī al Ghabar are commonly steeply dipping; isoclinal folding, and in places, overfolding, is present. Intense cleavage and fracturing of arenaceous strata are seen, but the rocks show no evidence of any mineral reconstitution.

Concerning the age and relation of the Wādī al Ghabar metasedimentary rocks to other basement-rock groups, the following points are noted. The low (dynamic) metamorphic grade of these rocks contrasts strongly with regionally metamorphosed rocks of Wādī Gharīsh, some 25 miles to the west, and with gneissic rocks of the Wādī Ḥajr area some 6 miles to the southwest. This difference could be due to deposition of the Wādī al Ghabar rocks after the main episode of regional metamorphism. Grounds for suggesting that older volcanic rocks of E.A.P. were extruded later than this period of regional metamorphism have been noted previously. These volcanic rocks

evidently predated, at least in part, the Wādī al Ghabar rocks; they underwent prior denudation, and volcanic material so derived is incorporated in conglomerates of the sedimentary series. As the older volcanic extrusive period is tentatively equated with intertectonic intrusive activity in the W.A.P., deposition of Wādī al Ghabar sediments is assumed to postdate this phase. The sedimentary rocks were subsequently affected by the widespread dynamic metamorphism which produced deformation and cataclasis in all the basement rocks of the region, excepting only the posttectonic intrusive rocks. A granitic representative of the posttectonic intrusive rocks, exposed in Wādī al Ghabar, gives an apparent age of 562 m.y. This, together with the absence of any recorded organic remains in Wādī al Ghabar rocks, indicates a Precambrian age for the Wādī al Ghabar rocks. To exactly which period of the Precambrian they belong cannot be deduced. It is relevant, however, that age determinations on Saudi Arabian rocks give no apparent age in excess of 1,000 m.y. (Brown and Jackson, 1960). Determinations on basement rocks from W.A.P. and the former Somaliland Protectorate, made by Suelling of the O.G.S. Age Determination Unit, have as yet yielded no apparent ages in excess of some 620 m.y. (written commun., 1964). (The last date may perhaps reflect the latest period of metamorphism in the region.) While these results do not provide direct evidence as to the age of the exposed basement rocks of the Arabian shield, they do suggest that the rocks are of later Precambrian age. Since the Wādī al Ghabar rocks appear to belong to the uppermost basement rocks of the Protectorate, it may be inferred that they are probably of latest Precambrian age. Further, on the grounds of metamorphic grade, lithology, and relation to (older) basement metamorphic rocks, the Wādī al Ghabar rocks may be tentatively correlated with the Fatima Series of Saudi Arabia (Karpoff, 1957) and through these with the Saramuj Series of former Trans-Jordan (Quennell, 1951). This may also support the postulation of a latest Precambrian age for the Wādī al Ghabar metasedimentary rocks.

The structural relations of the Wādī al Ghabar rocks suggest that these may be preserved in down-faulted areas. These rocks have not been recorded in W.A.P. It is possible that they were not deposited there; alternatively, and perhaps more likely, they may have been removed by denudation. The presence of spilites and keratophyres in the older volcanic rocks of E.A.P., possibly indicating formation in a basinal environment, accords with the idea that metasedimentary rocks of Wādī al Ghabar may have

been deposited in a structural depression originating during the same general period of downwarping.

According to the views expressed above, metamorphic rocks of Wādī Gharīsh are to be included in the Aden Metamorphic Group that is widely exposed in W.A.P. Older volcanic rocks of E.A.P. are considered to be of later date and are correlated broadly with the phase of intertectonic intrusive activity in W.A.P. Rocks of Wādī al Ghabar (and associated members of Beydoun's Ghabar Group) are regarded as the latest basement rocks of the area, and probably of youngest Precambrian age.

This interpretation differs from that provisionally advanced by Beydoun (1960, 1961), who suggested that rocks of the Ghabar Group are to be correlated with those of Wādī Gharīsh, a westward increase in metamorphic grade being due to regional tectonic factors. Because the older volcanic rocks (Tha'lab Group) predate Ghabar Group rocks, it would follow, according to Beydoun's views, that these are older than Wādī Gharīsh rocks, and as noted, Beydoun regarded the volcanic rocks as the oldest exposed rocks of the area. On the basis of data obtained during the recent O.G.S. survey, the interpretation advanced in this report is preferred, but firm conclusions are not justified.

METAMORPHISM

At least two major phases of metamorphism have been recognized in basement rocks of the Aden Protectorate, substantiated by clear evidence of polymetamorphism in petrographic specimens. The main phase was of dynamothermal (regional) metamorphism, the effects of which were significantly augmented by extensive and broadly contemporaneous granitic invasions concentrated at a number of focal points over the territory. An important phase (or phases) of mainly dynamic metamorphism occurred at a later date. Local thermal or contact metamorphism is recorded and is due mainly to later granite intrusion, and to a lesser extent to dike intrusion.

Foliation is generally axial planar to isoclinal folds and was caused by metamorphic recrystallization. Strain-slip cleavage attributed to the later period of stress is present both in older metamorphic rocks and later members of the basement complex. In the older rocks this cleavage does not obliterate previous structures, which are expressed in some places as contortions of earlier schistosity.

DYNAMOTHERMAL METAMORPHISM

The effects of dynamothermal metamorphism of mainly mesozonal type are expressed over a wide area extending from southwestern Hudhramut to the vicinity of Thawr al Bahā in the west. The highest grade

of metamorphism recorded is that represented by the staurolite-almandine subfacies of the almandine-amphibolite facies, as indicated in pelitic schists. Pelitic representatives of this grade were noted mainly in the eastern region; wadi concentrates from here show a few grains of kyanite. No sillimanite is recorded.

Apart from some of the earlier representatives of syntectonic granite, which may have undergone recrystallization during phases of renewal of the main regional metamorphic episode, the rocks affected by dynamothermal metamorphism constitute the Aden Metamorphic Group. Pelitic rocks are exemplified by garnet-muscovite-biotite schist from As Sufāl, Wādī Ḥabbān. This rock, in which garnet porphyroblasts are common, shows polymetamorphism in the crumpling of a previous schistosity, the presence of two generations of quartz and mica, and the bending of mica microporphyroblasts. Garnet-staurolite schist of Wādī Gharīsh, E.A.P., demonstrates relic bedding at a high angle to schistosity. This is also seen at Al Musaymr and elsewhere in the Protectorate.

Psammitic rocks interbanded with pelitic types showing dynamothermal metamorphism include quartzofeldspathic schists and gneisses in which sericitization is marked. Most of these are derived from quartzofeldspathic or arkosic sedimentary rocks; some may be derived from altered granites. Other psammitic rocks include widely occurring recrystallized quartzite, quartz schists, and garnet granulites of sedimentary origin. A banded garnetiferous muscovite psammite from the Nūṣāh area shows recumbent microfolds which indicate that the banding results from pinched out similar folds. Polymetamorphism is again shown by contortion of a previous schistosity.

Rocks of calcareous type, including those derived from impure siliceous and magnesian limestone, are represented by tremolite schists, plagioclase-diopside-scapolite gneiss, phlogopite-tremolite marble, and widely occurring crystalline limestone, many of which are dolomitic. Quartz-hornblende-epidote-chlorite schist from Wādī Gharīsh, E.A.P., represents metamorphosed impure dolomite.

Amphibolitic schists and gneisses occur commonly throughout the basement-rock areas and show a characteristic hornblende-plagioclase assemblage, including biotite and some garnet. These, together with hornblende schists, epidote-antinitolite-hornblende schists, and hornblende-chlorite-epidote schists, are considered to result mainly from dynamothermal metamorphism of mafic intrusive and volcanic rocks, but some altered calc-argillaceous sedimentary rocks may be represented. Polymetamorphic effects, such as the breakdown of hornblende under deformation, are shown in many of the rocks examined. A diopside-plagioclase gneiss

from the Kirsh area shows an assemblage indicating an original mafic igneous rock, probably a banded gabbro. A hornblende pyroxenite from Wādī Gharish, E.A.P., is regarded as an altered ultramafic rock. This rock shows deformation and hydrothermal alteration.

METAMORPHISM AND GRANITIZATION

The basement rocks are subject to abrupt variation in metamorphic grade; within short distances, in some places within half a mile, rocks of the lowest greenschist facies may be replaced by those of the almandine-amphibolite facies. This variation might be accounted for by the assumption that part of the Aden Metamorphic Group is of later origin and was subjected to metamorphism of epizonal type only; however, no unconformities have as yet been recognized in the group as at present defined. The observed variation could alternatively be related to the incidence of syntectonic granitic invasion, which, as noted, occurs at numerous focal points.

Temperature elevation associated with granite invasion is accepted as a major factor (if not the prime cause) in metamorphism of higher grade, and in this context it is immaterial whether emplacement is in the form of magma or migma, or a combination of both. There is evidence that metamorphism unaccompanied by syntectonic granitization results in rocks showing only a low (epizonal to lower mesozonal) grade of alteration (see Read, 1957, p. 342-344).

Field observations show that syntectonic granites form centers around which metasomatic alteration and enhanced metamorphic effects form approximately radial zones. It is suggested that the observed variation in metamorphism of the basement rocks was largely controlled by the incidence of granite invasion, which caused elevation of the grade of initially low-grade metamorphosed geosynclinal sedimentary rocks and associated mafic igneous rocks. Metacalcareous rocks occur commonly in the Aden Metamorphic Group, and these, with similarly widely occurring quartzites, form resistant bands in many granitic areas. These rocks may have formed barriers to metasomatism and granitization, thus contributing to the disparity in metamorphic grade from one locality to another.

Polymetamorphic and deformational effects seen in the rocks of the Aden Metamorphic Group are probably largely the result of a later period of dynamic metamorphism. There is, however, nothing to preclude such dislocation metamorphism being in part related to the main regional metamorphic phase, which would then embrace both dynamothermal and dynamic effects, the dominance of one or the other being related to the incidence of granitic invasion.

There is some evidence of retrograde metamorphism;

for example, in certain pelitic rocks, it is suggested by the breakdown of garnet that lacks crystal outlines and is marginally altered to chlorite. Amphibolization of diopside and other pyroxenes, epidotized pseudomorphs, chloritized biotite, and possibly some serpentinization may also be attributed to this process.

DYNAMIC METAMORPHISM

In rocks of the Aden Metamorphic Group a later phase of metamorphism is shown by contortion of previous schistosity and in other effects of deformation. Petrographic study indicates that this later metamorphism was of epizonal type, of a grade appropriate to the lower part of the greenschist facies.

By reference to the older metamorphic rocks alone, it is possible to infer only that a renewal of stress occurred, causing metamorphism mainly of dynamic type. This might be attributed to a late phase of the main regional metamorphic episode. The metamorphic state of later rocks suggests, however, that dynamic metamorphism occurred at a separate and later period. Thus dioritic rock in the Mukayras district contains inclusions of older metamorphic rock and is clearly of later intrusive origin. As opposed to dioritic and gabbroic derivatives in the Aden Metamorphic Group, which are now represented by hornblende-plagioclase gneiss, hornblende schists, and similarly reconstituted rocks, the later intrusive diorites and other intertectonic rocks are characterized by deformation, cataclasis, and shearing; they show no advanced regional metamorphism. It is clear that they were emplaced after the regional metamorphism but were affected by later dynamic metamorphism. The dynamic metamorphism has also affected rocks of Wādī al Ghabar in E.A.P., causing isoclinal folding, intense cleavage and fracturing, but no mineral reconstitution. The Wādī al Ghabar rocks are considered to represent the uppermost basement rocks of the Protectorate and to be of late Precambrian age. It seems clear that a phase of dynamic metamorphism occurred toward the close of Precambrian times.

No evidence has yet been seen to support the assumption of more than two main periods of folding. It is possible therefore that the dynamic metamorphism expressed in basement rocks over the whole area may be attributed to a period of stress in late Precambrian times. In this connection it is noted that age determinations on metamorphic rocks of the Aden Metamorphic Group give no apparent ages greater than 620 m.y. This may indicate a period of metamorphism at, or shortly before, this date; that is, the apparent dating may refer to the last main metamorphic phase.

Reference has already been made to the evidence of dynamic metamorphism in rocks of the intertectonic

intrusive group and in older volcanic rocks of E.A.P. (see under relevant subsections of basement-rock units).

THERMAL METAMORPHISM

Thermal metamorphism connected with the intrusion of granite plutons and dike rocks is demonstrated in many areas. A noteworthy example is the result of posttectonic granite of the Burūm area which intrudes andesitic volcanic rocks. A thermal aureole, some 18 inches wide where examined, is marked by andesite hornfels showing no directional fabric.

Thermal metamorphism of calcareous rocks is illustrated by the occurrence of idocrase-wollastonite marble at Al'Anad. Calc-silicate rocks and ophiolites are recorded from several areas, for example, Wādī Milh southwest of Lawdar.

Thermal imposed upon dynamothermal metamorphism is indicated by such effects as biotite and other porphyroblasts orientated across schistosity, as in Wādī Aḥwar and Wādī Gharish, E.A.P.

SYNOPSIS OF BASEMENT-ROCK GEOLOGY

In the following account, rock groups are treated as far as possible in chronological order; some interpretation of the probable geological history is included. The main divisions of basement rocks are summarized in table 3. The area of basement rocks in the Protectorate is about 8,500 square miles, excluding outcrops of small extent at Ra's Sharwayn. By far the greater part is exposed in W.A.P. in two areas of very unequal size. The main area is separated from Jurassic and younger sedimentary rocks to the east by a zone of faults that extend northwest from the locality of 'Irqah. It is bounded on its northern sector by the Ramlat as Sab'atayn and the Yemen border, and on the west by the Aden Trap Series, from which it is separated by a fault zone extending northwest from a point in the coastal plain north of Aden. The second and smaller area of basement rocks lies to the northwest of Aden. It is flanked to the east and west by volcanic rocks and on the south by the coastal plain; it extends northward across the border into Yemen.

Apart from relatively narrow, elongate outcrops of Jurassic and Cretaceous sedimentary-rock that occur in the coastal region, the main basement outcrop is concealed over an extensive area by basalt flows extending inland from the coast between Shuqrah and Aḥwar.

In the Eastern Protectorate the main basement outcrops occur in the Jibāl al Aswad to the northeast of Mayfa'ah, and in the general coastal area between the longitudes of Balḥāf and Al Mukallā.

TABLE 3.—Main divisions of the basement rocks
(In order to show all major plutonic intrusives, alkaline granite of post-Jurassic age is included. Post-Jurassic extrusive igneous rocks are omitted.)

Age	W. A. P.	E. A. P.
Late Cretaceous to Tertiary	ALKALINE GRANITE	
	Planation	
Age uncertain, possibly early Paleozoic	DIKE ROCKS	
	LATER MAFIC INTRUSIONS	
Early Paleozoic	POSTTECTONIC CALC-ALKALINE GRANITE	
		GHABAR GROUP
		Lightly metamorphosed sedimentary rocks and volcanic derivatives. Includes conglomerate, quartzite, sandstone, shale, limestone, and tuffaceous rocks
PreCambrian (latest)		
	Planation(?)	
	INTERTECTONIC IGNEOUS ROCKS	
	Dike rocks intruded mainly at a late phase of intertectonic igneous activity	
	Calc-alkaline granite. Contaminated rocks of Mukra'ah area. Intermediate mafic plutonic intrusions	Older volcanic rocks—mainly andesites and keratophyres with pyroclastic rocks
PreCambrian (late)		
	SYNTECTONIC GRANITE	
	Subautochthonous concordant granite and granitized rock approximately corral with main phase of regional metamorphism. Associated pegmatites and kridpathic bands	
	ADEN METAMORPHIC GROUP	
	Regionally metamorphosed sedimentary and mafic igneous rocks, including volcanic representatives.	
	Planation(?)	
PreCambrian (earliest)	OLDER GNEISS	
	Orthogneiss of granitic composition	

Orthogneiss of granitic composition exposed near Thawr al Bahā and in the Ṣa'id and Niṣāb areas is thought to represent the oldest rock in the Protectorate. This older gneiss is apparently not associated with surrounding rocks of the Aden Metamorphic Group, and no inclusions of the latter have been found in the gneiss. The older gneiss shows evidence of having been invaded by later syntectonic granite. Evidence as to the status of the gneiss is not sufficient to support firm conclusions. It is tentatively suggested that the gneiss represents a deeper thoroughly reconstituted autochthonous gneissose granite, which formed a massive block resistant to later tectonic stress.

Metamorphic rocks of the Aden Metamorphic Group are the most extensive of the basement groups in W.A.P.; they also crop out in several areas of southwestern Hadhramut. The group includes metamor-

posed sedimentary and mafic igneous rocks, some being volcanic representatives.

Original sedimentary rocks were of arenaceous, argillaceous, and calcareous type and were of varying purity. The sequence of depositional phases has not been worked out, but alternations seem to have been relatively rapid. Arenaceous rocks occur commonly as belts and bands throughout the group. They are represented by pure recrystallized quartzite, quartz-sericite schists, quartzo-felspathic schists and gneisses derived from arkosic sandstone, and schistose grit.

Phases of calcareous deposition are indicated by widely occurring metacalcareous rocks, including calcite and dolomite marbles, ophalcalcites and calc-silicate rocks, and epidiosites. Tremolite schists and plagioclase-diopside-scapolite gneisses are recorded. Crystalline limestone or marble bands may vary greatly in thickness; thus, an aggregate thickness of several hundred feet of this limestone at Jabal ath Thaniyah may be contrasted with bands 4 feet thick in the Nūshan area. Metamorphism of impure siliceous and magnesian limestone is indicated.

Phases of argillaceous deposition are shown by the widespread occurrence of pelitic rocks such as biotite and muscovite-biotite schists. These commonly are garnetiferous and may also contain staurolite, notably in the eastern region.

Metamorphosed mafic igneous rocks, derived from intrusions into the original sedimentary rocks, make up a large part of the basement complex. Amphibolites, hornblende-plagioclase gneisses, and hornblende schists are widespread. Diopside, as well as biotite and sparse garnet, is found in some of the specimens examined. Metamorphism of gabbroic and dioritic rocks is indicated. Altered ultramafic rocks appear to be of very restricted occurrence; they are represented by hornblende pyroxenite of Wādī Gharish, E.A.P.

Volcanic derivatives of mafic to intermediate composition are represented by epidote-actinolite-hornblende schists, by hornblende schists containing much epidote and albited plagioclase, and by chloritic green schists. The altered volcanic rocks are apparently mainly of andesitic type, but altered spilites are also indicated. Because distinction between metamorphosed mafic intrusives, volcanic derivatives, and impure calcareous rocks is not often possible, the relative abundance of these components is in doubt.

The thickness of the Aden Metamorphic Group, as estimated from the photogeological map, ranges between 30,000 and 40,000 feet. This estimate is an average of a number of sections, to which correction for dip has been applied, but in view of uncertainties as to the effects of folding and faulting it must be

regarded as little more than an informed guess. Estimates for apparently comparable rock groups in Saudi Arabia indicate thicknesses of as much as 37,000 (Brown and Jackson, 1960) or 50,000 meters (Karpoff, 1960). For Egypt, Schurmann (1961) suggested 7,000-12,000 meters (about 23,000-39,000 ft).

The metamorphic rocks are strongly folded, generally in isoclinal folds of similar type. Planes of schistosity and foliation dip generally but not invariably at high angles between 30° and 60°. Belts of very steep to vertical dip have been mapped, such as between 'Ataq and As Sufāl and parallel with Wādī Durā in the region to the south of Khawrah. Complicated fold structures, some involving overturning, are present (these are referred to under "Structure"). Foliation commonly is parallel with the axial planes of folds and with relic bedding, the latter being expressed by color banding or by mica- and garnet-rich layers. In some places however, marked divergence between relic bedding and foliation strike is seen, as in Wādī Gharish and near Al Musaymir. The rocks show clear evidence of polymetamorphism and were evidently subjected to at least two metamorphic phases. Of these, the main phase—of dynamothermal type—resulted in grades reaching that represented by the almandine-amphibolite facies, as shown by pelitic rocks with garnet and staurolite. Marked variation in metamorphic grade is seen, however, and in some areas metamorphic rocks of the group are represented by quartz-chlorite-epidote rocks of the low greenschist facies. This variation is attributed mainly to the incidence of syntectonic granite invasion, a relation between foci of invasion and elevation of metamorphic grade being demonstrated in a number of areas. A later period of metamorphism, of essentially dynamic type, resulted in rocks belonging to the lower greenschist facies. The main period of regional metamorphism is associated with Precambrian orogenic moves whereas the later dislocation metamorphism is attributed to directed stress in late Precambrian times, following elevation and denudation.

Within the Aden Metamorphic Group as at present defined, no unconformities have been recognized and no great differences in overall composition are apparent from one area to another. The variation in metamorphic grade possibly suggests the presence of a younger upper division characterized by low-grade (epizonal) rocks. On the basis of present data no major division of this kind could be upheld, however, because variation in grade of metamorphism does not provide a reliable criterion and is not necessarily related to depth zoning.

The Aden Metamorphic Group is tentatively cor-

related with the main part of the Medina Series of Saudi Arabia (Karpoff, 1960).

Syntectonic granite is in aggregate outcrop area the most extensive of the Protectorate granites. It invaded rocks of the Aden Metamorphic Group, giving rise to granitization and other metasomatic changes and affecting the grade of metamorphism over extensive zones centered on focal points of invasion. In summary, the granite appears to be intermediate between parautochthonous and true intrusive rock, representing partly mobilized magma-magma bodies displaced upward from katazonal levels. It is, in the main, foliated or gneissose, but in part it is of homogeneous nonfoliate type—the latter in the central zones. It is associated with variably developed but generally relatively restricted migmatitic areas. Extensive zones of feldspathization are a characteristic feature; these are marked by feldspathic bands, which may show pygmy folding, and by feldspar porphyroblasts present in country rock for considerable distances, commonly several miles, from the center of invasion. Pegmatites, bearing garnet and muscovite but apparently without pneumatolytic ore deposits, are found in the inner zones; quartz veins tend to occur mainly in the peripheral zones.

Conclusions as to the origin of this granite are based on the sum total of field relations, textural characteristics, and petrography. The granite is considered to have been formed approximately coevally with the culmination of the main period of regional metamorphism, to the effects of which the granitic invasion materially contributed.

Some major areas of this granite are 8 miles southeast of Al Kirsh, 15 miles northwest of 'Irqah, 8 miles southwest of Lawdar, about 12 miles south of Niṣāb, and also in Wādī Banā and Wādī Abwar.

Intertectonic igneous rocks are attributed to a phase of igneous activity that occurred later than the main period of regional metamorphism but prior to a period of dynamic metamorphism which was probably of late Precambrian date. The rocks are characterized by cataclastic and other deformation effects but show no evidence of higher grade dynamothermal metamorphism.

In W.A.P., intrusion of intermediate and mafic plutonic rock was followed, probably after only a short interval, by granitic intrusion.

Mafic igneous plutonic rocks are represented by altered dioritic and gabbroic rocks, generally without foliation but showing a partial development of schistosity in some localities. In the Mukayrās area unfoliated diorite is intrusive into hornblende-plagioclase gneiss and amphibolite of the Aden Metamorphic Group and contains inclusions of these older rocks.

The main outcrops occur in a broad belt between Mukayrās and Khawrah. More limited exposures were recognized some 12 miles northeast of Bayḥān and in Wādī Mill, 14 miles southwest of Lawdar.

Granitic rocks of the intertectonic period form most of the Mukayrās granite area and include rocks described as calc-alkaline granite and hornblende adamellite (alkaline granite, probably of later date, has also been found in the Mukayrās area). That the intertectonic granite of this area postdated mafic intrusions is shown by the presence of dioritic inclusions in the granite, and reaction between granitic material and somewhat earlier mafic rock has resulted in contamination and the production of hybrid rocks. On the southern periphery of the Mukayrās granite is some evidence for progressive zonal changes, hornblende granite passing through granodiorite to quartz diorite, or tonalite, and finally to hornblende diorite. There is also some indication that the central part of the granite is more biotitic and less hornblende than the peripheral part. Further work is necessary to confirm this.

Intertectonic granitic rocks also occur in the Khawrah district where nonfoliate hornblende granite contains inclusions of dioritic rock, as at Mukayrās. Deformed syenite in this area is apparently intrusive through diorites. Granodiorite cropping out near Jabal ath Thaniyah is also thought to be of intertectonic type.

Both mafic and granitic intrusions of the intertectonic period show the effect of dislocation metamorphism by features such as deformed and bent crystals, deformation cracks, shattered and strained quartz, and shear lines visible in thin section. Numerous zones of shearing are seen in sections exposed in the locality of the Mukayrās pass.

Older volcanic rocks are exposed over extensive areas in the Eastern Protectorate, notably at Ḥulm Bā Tha'lab, along the coast, and inland between Ra's ar Rujaymah and Burūm. These consist of a thick series of lavas including andesites, keratophyres, soda rhyolites, and less commonly, trachytes. Pyroclastic rocks are associated with the lavas. The rocks have been intensely cleaved and fractured, and are serpentinized and epidotized. They show little evidence of any higher grade dynamothermal metamorphism and in this respect contrast with volcanic derivatives in the Aden Metamorphic Group which are reconstituted schistose rocks. At least in part, the older volcanic rocks predate the sedimentary rocks of Wādī Ghabar and are intruded by later granites that show no deformation (posttectonic granites). They are considered to represent an extrusive phase approximately contemporaneous with the intertectonic intermediate mafic intrusions of the W.A.P. The absence of these volcanic rocks in W.A.P. (as also of metasedimentary rocks of

Wādī Ghabar type) may be due to denudation in earlier early Paleozoic times.

Lightly metamorphosed sedimentary rocks exposed in E.A.P. in Wādī al Ghabar and in Wādī Minḥamir and Wādī Bā 'Aryat constitute the Ghabar Group of Beydoun (1961). The composition of this group is summarized on page C31. Salient features include (a) the presence of volcanic derivatives in conglomerates at or near the base of the group and in interbedded tuffaceous horizons and (b) the presence of platy limestones with gypsum indicating shallow evaporitic conditions. Arenaceous rocks make up a large part of the sedimentary assemblage. The presence of volcanic derivatives which can be matched in older volcanic rocks of the area supports the conclusion that the Ghabar Group was derived by denudation of older basement rocks of the region and was deposited in one or more relatively restricted basinal depressions. No organic remains have been identified within the group, and shales tested palynologically proved barren.

The rocks of the Ghabar Group are strongly—commonly isoclinally—folded; over-folding and local thrusting are recorded. Intense multidirectional cleavage is present and arenaceous strata show marked fracturing, but, with the possible exception of an isolated occurrence of greenschists recorded by Beydoun in Wādī Bā 'Aryat and attributed by him to small-scale thrusting (Beydoun, 1961), the rocks show no sign of mineral reconstitution.

The metasedimentary rocks of the Ghabar Group appear to represent the uppermost basement rocks of the region. On the evidence of age determinations from undeformed and presumably later posttectonic granite occurring in Wādī al Ghabar and elsewhere in the same general area, and on the absence of organic remains, it is probable that the metasedimentary rocks are of latest Precambrian age. Their tentative correlation with the Fatima Series of Saudi Arabia would accord with this view. It also is probable that the dislocation metamorphism undergone by the Ghabar Group reflects a widespread phase of dynamic metamorphism which affected all the basement rocks of the Protectorate toward the end of Precambrian times and which accompanied the final orogenic moves in the region. Subsequent moves were epeirogenic.

Posttectonic granite of calc-alkaline type occurs in W.A.P. in the areas of Lawdar-Mūdiyyah, Jibālan Jebel Nisīyīn, Sa'id, Niṣāb, Bayḥān, and Wādī al Kayfī (south-southwest of Al Musaymīr); and in E.A.P. at Burūm, Zulm Ash Shaybah, and Wādī al Ghabar. These granites show no significant deformation or cataclastic effects, and in a number of places form discrete crosscutting intrusions with well-marked thermal metamorphic aureoles, as at Burūm. These are

clearly high-level plutons. At Burūm, Wādī al Ghabar, and Mūdiyyah the intrusions are composite, a coarser gray granite preceding a finer red type.

Determinations made on granite from Wādī al Kayfī, Wādī al Ghabar, Burūm, and a locality some 10 miles northeast of Bayḥān indicate an early Paleozoic age.

Intrusions of mafic plutonic rock, which do not appear to have undergone significant metamorphism, include unalitized gabbro of the 'Ataq area, and leucogabbro of Jabal al Munīf, Al 'Anad. These rocks are of uncertain age; they may perhaps be connected with the phase of intrusive activity expressed mainly in posttectonic granites. The rocks of this group are referred to as later mafic intrusions.

Alkaline granite occurs at Jabal al Munīf (Al 'Anad) and on the Mukayrās plateau near Mukayrās. At Jabal al Munīf aegirine-riebeckite granite is intrusive into the volcanic rocks of the Aden Trap Series, of Late Cretaceous or Tertiary age. The riebeckite granite of Mukayrās cannot be dated in this way, but on petrogenetical grounds it is tentatively equated in age with the Jabal al Munīf intrusion.

Dikes of both silicic and mafic rocks cut rocks of the Aden Mukayrās Group in many localities. The dikes commonly show a moderate degree of metamorphism in which effects of deformation are prominent. Typical of such rocks is a 30-foot-wide dike of altered dolerite which cuts garnet-staurolite schist in Wādī Gharīsh, E.A.P. Pyroxene in this rock is largely unalitized and shows deformation, as do the slightly bent feldspars.

In the Mukayrās-Khawrah region dike rocks are very common. They are of doleritic and andesitic composition, and occur with felsites and quartz-feldspar porphyries. The dike range in width from about 6 to 150 feet. An altered dolerite cutting granite some 2 miles north-northeast of Mukayrās has undergone incipient greenschist metamorphism, and bent pyroxenes demonstrate the effects of stress. A porphyritic granophyre dike in the same area contains quartz full of shatter cracks. Many of the dikes in the Mukayrās area are later than the dioritic and granitic intertectonic rocks in which they occur, as shown by chilled margins against the granite and by inclusions of dioritic rock in andesite dikes of the Mukayrās pass.

Dikes affected by moderate dynamic metamorphism are considered to be of Precambrian age. They may have been intruded at various periods, but the great number of dikes associated with intertectonic rocks of the Mukayrās area suggests a major phase of dike emplacement connected with, and probably representing, a late phase of intertectonic igneous activity.

Dikes of microgranite and aplite, associated with

areas of granite throughout the Protectorate, are connected with one or another of the granitic invasive phases.

In addition to dikes showing some degree of metamorphism, there are those in which no sign of alteration can be detected. Apart from dikes associated with the volcanicity of the Aden Trap Series in the west of the Protectorate, none of these dikes is seen to cut Jurassic or later rocks. The undeformed dike rocks may thus be dated as pre-Jurassic, and probably of later than Precambrian age. These may be connected with lower Paleozoic granite intrusion. Dikes cutting the metasedimentary rocks of Wādi al Ghabar would fall into this category.

With regard to the history of the basement rocks the following interpretation is tentatively advanced.

The metamorphosed sedimentary rocks of the Aden Metamorphic Group represent geosynclinal deposits folded and metamorphosed during a Precambrian orogeny that was accompanied by broadly contemporaneous igneous activity. Interbedded metavolcanic rocks indicate extrusion of mafic to intermediate lavas, including some of spilitic type, during the geosynclinal phase of tectonism. Partly synchronous with this, and before the main period of regional metamorphism, intrusion of mafic, and more rarely, of ultramafic plutonic rocks occurred. This was followed by syntectonic granite invasion and granitization during the culminating and late phases of the main metamorphism. A later phase of mafic to intermediate igneous activity, represented by intertectonic igneous rocks, probably accompanied, and in part followed, elevation of the compressed zone. Mafic intrusions of this phase were soon followed by granitic intrusions, giving rise to contaminated or hybrid rocks in some areas. Following the phase of intertectonic igneous activity, renewed elevation of the compressed and metamorphosed geosynclinal rocks took place. This uplift was apparently intermittent, with periods of stillstand and concomitant local downwarping. Sediments of the type represented by the Ghabar Group were deposited at this time, probably in more than one basinal area of fairly restricted extent. No attempt can be made to define the locale of basin development, but it is likely that sediments of the Wādi al Ghabar type were also deposited in W.A.P. (as in other regions of Arabia and Somaliland) and were subsequently removed by denudation. Stress accompanying the last Precambrian orogenic moves resulted in widespread metamorphism of epizonal type which affected all Precambrian basement rocks.

The penepleaned basement rocks of the Protectorate are unconformably overlain by Jurassic and younger rocks, beneath which the basement rocks are weathered

to depths of at least 6 feet. Prior to the deposition of the sedimentary cover, the basement rocks underwent one or more periods of planation, and it is clear, from the metamorphic state of the basement rocks and the presence of exposed intrusive rocks, that a cover of considerable thickness has been removed. Regarding the nature of this cover, in relation to older metamorphic and intrusive rocks, there is no difficulty in inferring a cover of Precambrian rocks. However, other conditions must be satisfied. The Ghabar Group of metasedimentary rocks, representing the uppermost basement rocks of the Protectorate and regarded as of latest Precambrian age, are intruded by dike rocks. This indicated the presence of a superincumbent cover, since removed. Also, although in Aden Protectorate posttectonic granites (dated as early Paleozoic by radio active age determinations) do not cut the Ghabar Group, in former Somaliland Protectorate granite of similar age (Las Bar Granite) is intrusive into the Inda Ad Series, which is probably to be correlated with the Ghabar Group. It is likely that in Aden Protectorate, cover rocks younger than the presently outcropping Ghabar Group were present at the time of early Paleozoic granite intrusion. It is possible that an additional thickness of latest Precambrian rocks provided this cover, but the conditions under which the Ghabar Group sedimentary rocks appear to have been deposited do not suggest that the original thickness of this group could have been sufficient. The possibility of a cover of volcanic rocks must be considered. The presence of Paleozoic sedimentary rocks in central Arabia and Oman and the presence of presumed Cambrian sedimentary rocks upon the equivalent of the Ghabar Group in Jordan (Saramuj Series), however render it at least as likely that the Paleozoic sedimentary strata extended over the Aden Protectorate. This may be supported by some evidence from Yemen, where Geukens records a small outcrop of apparently Paleozoic metasedimentary rocks (Geukens, 1960, p. 162). Epirogenic elevation and tilting of the Arabo-Nubian shield, with which posttectonic igneous activity may be connected, would result in the denudation of this lower Paleozoic cover. The date of the planation(s) of the basement rocks remains, however, conjectural.

REGIONAL CORRELATION OF BASEMENT ROCKS

A review of the data on regions surrounding the Protectorate reveals significant similarities in the composition and history of development of basement rocks.

YEMEN

Basement rocks occurring in southeast Yemen, which comprise granite gneiss, strongly folded mica schists,

amphibolites, and quartzites, were referred to the Precambrian by Geukens (1960) and equated with Karpoff's (1957) Medina Series of Saudi Arabia. In northern Yemen, Geukens recorded at least two groups of folded rocks separated by an unconformity. The older more extensive group represents the Medina Series, and the upper series, of folded conglomerates, altered arkose, and quartzite, is the equivalent of Karpoff's Fatima Series.

Geukens concluded that the Medina Series underwent regional metamorphism during which important granite massifs were emplaced. These massifs were peneplaned and covered by equivalents of the Fatima Series. Traces of these remain only in the northwest part of the country. In contrast to the north strike of the older basement, a less important east-striking folding was imposed on these rocks.

Rocks of possible Paleozoic age were recorded by Geukens in a locality east of Sa'da, where a limited number of outcrops of slightly graphitic phyllitic rocks are distinguished by their metamorphic state from older basement rocks and from Jurassic rocks. Geukens considered it probable that the Paleozoic (Cambrian to Silurian?) transgression of Saudi Arabia extended into Yemen.

Karrenberg (1956) recognized that many of the granite and dioritic blocks of central and southern Yemen are of younger intrusive origin, emplaced in Upper Cretaceous to Tertiary volcanics. Most of these are of alkalic type, although calc-alkaline rocks also occur. Karrenberg concluded that the granitic intrusions are of Tertiary age, and being connected with a graben zone, they are not to be regarded as genuine plutonic rocks; rather, their occurrence under the same structural conditions as give rise to vulcanism lead to their being termed "volcano-plutons." The granites are said to be without mineral veins or zones, and were not associated with tectonic movements. A causal connection between the sinking of the Red Sea graben and the development of silicic from initially mafic magma is assumed, and it is thought that the granites may have been formed at relatively shallow depths. Alkaline granite of similar age occurs in W.A.P.

SAUDI ARABIA

Karpoff (1957, 1960) regarded the folded basement rocks of the Arabian Peninsula as being everywhere of Antecambrian age and he considered peneplanation to have occurred well before a Cambrian transgression. Basement rocks are divided into an older Medina Series and a younger Fatima Series; the existence of a third more ancient group is suggested by the presence of pebbles of gneiss and granite in the Medina Series.

The Medina Series includes dark lavas, mainly of

andesitic type, volcanic breccias, tuffs, and conglomerates; original sedimentary rocks are represented by various schists, amphibolites, marble, quartzite, and conglomerate. Migmatite and gneiss were also recorded. Granites of various ages crop out in the series; diorites, gabbros, and serpentines are of relatively restricted occurrence.

Between Riyadh and Jiddah the Medina Series was said to be possibly more than 50 kilometers thick. It has undergone varied degrees of metamorphism resulting in rock types ranging from chlorite schist to migmatite. The folding was said to be mainly simple, with schistosity parallel to stratification. Dominant strike directions approximate northwest and northeast, and this is also the general orientation of fold axes although some folding on north-south axes was recorded.

The Fatima Series consists of volcanic rocks, striped slates or schists, limestones, and abundant arkose and conglomerate. In the type area of Wadi Fatima a partial thickness of at least 500 m was recorded. The series is separated from the underlying Median Series by a major unconformity and the two groups are further distinguished by a contrast in metamorphic grade, which for the Fatima Series does not exceed that appropriate to the lower greenschist facies. The younger age of the Fatima Series is supported by the presence of *Stromatolites* at three horizons in slightly altered limestones. Folding is orientated from north to east-southeast; northwest fold directions are not known. The "schistosity" present in some of these slightly altered beds is in places oblique to stratification. The age of the series was said to be certainly pre-Maestrichtian, and probably Precambrian.

The following correlations were tentatively proposed by Karpoff. The Medina Series was equated with the Aqaba Granite Complex of Jordan, the Atalla-Mitiq Series of Egypt-Sinai, and the Nafideib Series of Sudan. The Fatima Series was correlated with the Saramuj Series of Jordan, the Hammamat-Dokhan-Ferani of Egypt-Sinai, and the Awat Series of Sudan.

The Saq Sandstone of northern Arabia was equated with the Quweira Sandstone of Jordan, and both were said to be of Cambrian age. (With reference to the age of the Saq Sandstone, Steineke, Brankamp, and Sauder (1958) recorded that *Crúziana*-like tracks are present in the upper part, but no diagnostic fossils have been found. They further stated that rocks of Cambrian age occur in the Al-Aqabah-Dead Sea area, dated by fossils, and that the Saq Sandstone has not yet been traced laterally into fossiliferous Cambrian rocks. The Saq Sandstone was, however, considered to represent the approximate lateral equivalent of Quennell's (1951) combined Quweira, Ram, and Um Sahin Series; these in turn were considered by Quennell

to include beds equivalent to the fossiliferous Cambrian rocks.)

Brown and Jackson (1960), in describing the segment of the Arabian shield in the highlands of western Saudi Arabia, noted gneissoid belts having no apparent intrusive relations with adjoining beds, which may represent the oldest rocks exposed (compare older gneiss of W.A.P., p. C14). Most abundant of the granitic rocks are granodioritic and adamellite types, mainly in synkinematic concordant batholiths. Age determinations for synkinematic granodiorites and related rocks indicated an apparent age of 1,000 m.y. Batholiths and stocks of calc-alkaline granite showing both concordant and discordant features were dated at about 710-750 m.y., and quartz diorite was dated at about 820 m.y. Injection granite about 600-640 m.y. in age was recorded. Soda-rich granitic, syenitic, and rhyolitic rocks occur as plugs, stocks, and ring dikes; these rocks are apparently unmetamorphosed and undeformed; a wide age span is suggested and periods of vulcanism of middle Paleozoic and early Tertiary date may possibly be represented. Small intrusive rocks of younger diorite and gabbro were reported in the foothills near the Red Sea rift zone and were referred to as late mafic rocks. (Comments on the age determination figures cited above are included in the section on "Age determination results.")

The Hali Schist Series, considered by Brown and Jackson to include the oldest metamorphic rocks, appear to be lithologically comparable with members of the Aden Metamorphic Group. The Baish Greenstone and Lith Complex, including greenstone, metadiorite, metagabbro, and amphibolite, may correspond to metamorphosed igneous rocks in the Aden Metamorphic Group. The Halaban Andesite Group of the central and northern Arabian shield area consists of less metamorphosed intermediate and silicic volcanic rocks with intrusive intermediate and mafic rocks. These appear to correspond to intertectonic igneous rocks of Aden Protectorate. Brown and Jackson equated their Fatima and Abba Formations with Karpoff's Fatima Series. These slightly metamorphosed beds, occurring in isolated basins, were said to be gently folded, and were referred to the Precambrian. They are separated from underlying rocks by an obvious unconformity.

EGYPT

Schürmann (1961) considered the Precambrian rocks of the Red Sea region to belong to the youngest consolidated rim of the African cratonic shield. He compared them with the Riphean of Russia (Schatsky, 1960), which in the Ukraine is dated as about 570-630 m.y. and lies beneath unconformable fossiliferous

Lower Cambrian. Reviewing results of age determinations, Schürmann suggested that the rocks of the Red Sea region are generally about 600 m.y. old and thus contrast with the Precambrian (Archaean) of the older parts of the African shield. He recognized in western Saudi Arabia and the Eastern Desert of Egypt two eugeosynclines, or two parts of one larger geosyncline, in which intense folding in the center gives way to block faulting on the shallower rim. Granitization and migmatization of katazonal sedimentary rocks in the center of the trough were recorded.

From Schürmann's account of the older rocks of Egypt, a tentative correlation with the Aden Protectorate rocks may be attempted. This is summarized in table 4. The Shaitian (syntectonic) Granites of Egypt appear to be the counterpart of Aden syntectonic granites; similarly the older Gattarian of Egypt, composed of granites and dioritic rocks, may perhaps be equated with intertectonic intrusive rocks of the Protectorate. The older Gattarian rocks are separated by an unconformity from overlying Hammamat Series, which was equated by Schürmann with the Saramuj Series of Jordan and with the Inda Ad Series of former Somaliland Protectorate.

A general correspondence between the Precambrian of Egypt and that of Aden Protectorate is also apparent from Said's (1962) account of Egyptian rocks, from which may be noted the statement that regional metamorphism of original sedimentary rocks was accompanied by metamorphism and granitization, resulting in Shaitian granites.

EASTERN ADEN PROTECTORATE

In an account of the stratigraphy and structure of Eastern Aden Protectorate, Beydoun (1961) described basement rocks cropping out mainly in southwestern Hadramawt and also at Jabal ath Thanyah near the Yemen border. A group of older volcanic rocks, named by Beydoun the Tha'lab Group were considered by him to represent the oldest exposed rocks in E.A.P. A series of sedimentary rocks with some volcanic rocks, which have undergone regional metamorphism to the albite-epidote-amphibolite facies reaching grades with garnet and staurolite as index minerals, occurs in the Gharish-Madbi area of E.A.P. This series represents Beydoun's Gharish Group, comprising various schists, amphibolites, quartzites, and marbles. Beydoun suggested that the Gharish Group may be equivalent to virtually unmetamorphosed rocks of the Ghabar Group that crop out some 40 km to the east. The transition cannot be followed in the field but is attributed to increasing metamorphism from east to west.

TABLE 4.—*Tentative correlation of basement and certain other rock units of Arabia and bordering regions*

AGE	Aden Protectorate		Saudi Arabia	Yemen	Former Somaliland Protectorate	Egypt	Former Trans-Jordan
	Western	Eastern					
Tertiary	Alkaline Granite.		Representatives of Late Alkaline Rocks (Brown and Jackson, 1960).	Granitic intrusions mainly of alkalic type (Karrenberg, 1956).		Tertiary(?) plutonium (Higazy and El Hamly, cited by Schürmann, 1961).	
Early Paleozoic	Posttectonic calc-alkaline granites		Posttectonic Granites (Karpeff, 1960). Representatives of Late Alkaline Rocks, including granite. Shammur Rhyolite (Brown and Jackson, 1960).	Certain intrusive Granites (Geukens, 1960).	Posttectonic "Younger" Granites including Iaa Bar, Afar, and (?) Dalmoleh Granites.	Younger Gattarian including granite (Schürmann, 1961).	
Cambrian			Saq Sandstone (Guttenberg, Bramkamp, and Sander, 1956).	Paleozoic(?) phyllitic rock (Geukens, 1960).			Quweira Series, mainly arenaceous and conglomeratic (Quennell, 1961).
Late Precambrian		Ghazal Group (Beydoun, 1961).	Fatima Series (Karpeff, 1957, 1960). Fatima and Abba Formations (Brown and Jackson, 1960).	Fatima Series equivalents (Geukens, 1960).	Inda Ad Series.	Hammamat Series (Schürmann, 1961).	Saramuj Series (Quennell, 1961).
Precambrian	<i>Inter-tectonic igneous rocks</i> Intermediate mafic intrusions followed by granitic intrusions. Hybrid rocks of Mukhras-Khawrah.	<i>Inter-tectonic igneous rocks</i> Older volcanic rocks (equal to) Thabab Group of Beydoun, 1961.	Upper part of Medina Series (Karpeff, 1960). Calc-alkaline Granite Series and Halaban Andesite (Brown and Jackson, 1960).	Components of Medina Series equivalents as described by Geukens (1960).	Mafic Intermediate intrusions followed by granite intrusions (Mason and Warden, 1966; Gellatly, 1960). Hybrid granite-gabbro, Bushah gabbro (Hunt, 1960).	Older Gattarian-granite and dioritic rock. Dokhan Series (Schürmann, 1961).	(?) Pink Granite of Aqaba Granite Complex (Quennell, 1961).
	<i>Syn-tectonic granite</i> Concordant granites and granitoid rocks, approximately coeval with the main phase of regional metamorphism. Pegmatites and felspathic bands associated with granitic rocks.		Syn-tectonic Granite (Karpeff, 1957). (?) Syn-tectonic granodiorite and related rocks (Brown and Jackson, 1960).	Granite massifs emplaced during regional metamorphism (Geukens, 1960).	Syn-tectonic Granite (Gellatly, 1960). Metasomatic granite (Mason and Warden, 1966).	Shaitan Granite Granodiorite, foliated in part (Schürmann, 1961). Metasomatically Older (Shaitan) Granites (Said, 1962).	Gray Granite of Aqaba Granite Complex (Quennell, 1961).
	<i>Aden Metamorphic Group</i> Regionally metamorphosed sedimentary and mafic igneous rocks, and volcanic representatives, including Beydoun's (1961) Ghazal and Thaniya Groups.		The major part of Medina Series (Karpeff, 1960). Hali Schist, and Bahl Greenstone and Lith Complex (Brown and Jackson, 1960).	Medina Series equivalents (Geukens, 1960).	Metamorphic rocks of the Basement Complex—metamorphosed sedimentary, volcanic, and mafic igneous rocks including Kalaba, Hudud and Barkasan Series (Hunt, 1960).	Old Paracrusts including volcanics. Atalla Series—metamorphosed sedimentary and volcanic rocks (Schürmann, 1961).	Metamorphic rocks of the Aqaba Granite Complex (Quennell, 1961).
Earlier Precambrian	Older Gneiss.	(?) Evidence of Older Gneiss in derived pebbles.	Orthogneiss of Gneiss belts (Brown and Jackson, 1960).		Older Granite Gneiss. Dair-Iding Series, mainly gneissic Granite (Hunt, 1960).	Mittig Feiran Gneiss. (Schürmann, 1961).	

Metamorphic rocks exposed in the area of Jabal ath Thaniyah were named by Beydoun (1961) the Thaniya Group. He noted that Thaniya and Gharish Group rocks represent about the same grade of metamorphism and suggested that the two may be lateral variants. However, on the grounds that the thick-bedded calcareous rocks of Jabal ath Thaniyah are absent in Wādī Gharish, he believed that the Thaniya Group may represent an older sedimentation that marked the start of a sedimentary cycle later completed farther south in E.A.P. and W.A.P.

Slightly metamorphosed sedimentary rocks occurring in Wādī al Ghabar and elsewhere in this locality were named the Ghabar Group. These are described on pages C31-C32. At Wādī Minḥamir a basal formation of the group, consisting mainly of pyroclastic material, rests unconformably upon Tha'lab Group volcanic rocks. Isoclinal folding of the sedimentary rocks is not accompanied by any mineral reconstitution.

Beydoun considered that formation of the volcanic Tha'lab Group mainly predated deposition of the Gharish and Ghabar Groups, but suggested that deposition of the Thaniya Group may have been initiated before the extrusive activity and that deposition and extrusion may have then proceeded concurrently. Volcanic rocks in the upper part of the Thaniya Group were thought possibly to relate to the same period of vulcanicity as resulted in the Tha'lab Group of southwestern Ḥaḡramaut.

The exposed basement rocks of E.A.P. are assumed to rest upon an older metamorphic series exposed to the west, which in turn overlies a more massive basement assemblage that is not exposed. A tentative correlation of W.A.P. basement metamorphic rocks with the Medina Series (of Saudi Arabia) was suggested by Beydoun (1961).

The tentative conclusions reached by Beydoun are supported by further observations too numerous to recount here. Following the study of the W.A.P. basement rocks made in the recent survey, however, the present authors are led to suggest alternative relationships for the E.A.P. basement groups. Reference to the Tha'lab Group volcanic rocks is made elsewhere in this contribution (p. C40), where reasons are given for dissenting from the view that these rocks predated regionally metamorphosed rocks of the area, and for suggesting their equivalence to the intertectonic igneous rock of W.A.P. The metamorphic rocks of Wādī Gharish appear to be similar in all respects to those exposed over wide areas of W.A.P.; they are therefore included in the Aden Metamorphic Group. Although the last is to be tentatively correlated with the Medina Series (as remarked by Beydoun), the metasedimentary rocks of the Ghabar Group are thought to be of latest

Precambrian age and to be equivalent to the Fatima Series of Saudi Arabia.

FORMER SOMALILAND PROTECTORATE

During the last decade, much work has been done on the basement rocks of this region, most of which is recorded in published and unpublished reports of the former Somaliland Protectorate Geological Survey. No generalized account has been seen, but a review of the work of various authors discloses several points on which a fair measure of agreement exists. The following synthesis results from interpretation of their reports.

Pre-Jurassic rocks may be initially divided into two major classes, namely, an extensive series of igneous and metamorphic rocks and a more restricted series of lightly metamorphosed sedimentary rocks typified by the Inda Ad Series of the northeast coastal area. Reference to basement rocks in the following discussion does not include the Inda Ad Series unless specifically stated.

Basement rocks of former Somaliland Protectorate contain a large proportion of metamorphosed sedimentary rocks including psammites, pelitic rocks, and metacarcareous rocks. Psammites appear to be dominant, and observations in several areas suggest that these may be basal to the metasedimentary succession, being followed by pelitic or semipelitic rocks. At least in some areas, metacarcareous rocks are sufficiently concentrated at higher levels to warrant postulation of an uppermost limestone series, for example, in the Hargeisa District (J. L. Daniels, unpub. data, 1959). However, marble and other metacarcareous rocks are distributed throughout the succession.

The widespread occurrence of plagioclase amphibolites in metamorphosed sedimentary rocks, notably in the pelitic series, is fairly generally agreed to indicate altered mafic intrusive rocks, and these for the most part were intruded prior to regional metamorphism (J. E. Mason, unpub. data, 1954). Representatives of metamorphosed mafic volcanic rocks have been recorded in the pelitic series, and in the Borama District Mason suggested that certain chlorite schists and aphanitic amphibolites may be the products of contemporaneous submarine vulcanism. Metamorphosed rhyolites appear to occur near the top of the basement succession. W. C. White (unpub. data, 1955) recorded sheared mafic volcanic rocks and rhyolites in the pelitic series of the Western Borama District.

Synorogenic granite emplacement is substantiated in numerous areas and granitic invasion in a number of stages is recognized. References to migmatization and to the development of granite *in situ* are numerous. The latter is variously attributed to anatexis, meta-

somatism, or granitization, and is particularly associated with psammitic rocks. White (unpub. data, 1955) stated that many of the rocks of Western Borama District are the product of the admixture of granitic fluids with sedimentary or mafic igneous rocks, and he considered anatexis to mark a late stage of regional metamorphism. Hunt (1958), reporting on the geology of the Adadleh area, referred to granitized rocks of the Daarbuduq Series and granitized psammites of the Kalaha Series which are in places completely converted to granite. A similar transition through granitoid rocks to granite has been reported from many areas. Feldspathization around granite centers has been recorded; for example, A. J. Warden (unpub. data, 1959, on basement rocks of areas in the Berbera District) referred to extensive feldspathization of metasedimentary rocks surrounding a main granite mass. It may be concluded that the development of granite or granitic rock from metamorphosed sedimentary rocks by the process generally described as granitization is a major feature of the basement geology. The majority of authors correlated the main phase of granite invasion and granitization with the culminating or late stages of regional metamorphism. Hunt (1958), however, recognized granitization at various stages in the history of the basement rocks.

Mafic intrusions, including diorite and gabbro, appear to have postdated the main syntectonic granites (see Gellatly, 1960, p. 33, on the Las Dureh area). Mafic rocks have been intruded by later granite, and marginal hybridization or contamination has occurred, as recorded by Hunt (1958) near Sheikh; rock types so produced include quartz diorite and syenodioritic rocks.

Posttectonic granites of clearly intrusive type are known from a number of areas, for example the Las Bar granite of the Elayu area (Greenwood, 1960).

Over much of the basement-rock area metamorphism in the lowest subfacies of the almandine-amphibolite facies seems to be dominant, but there is evidence for advance to the granulite facies in certain areas. Metamorphism in the greenschist facies is shown in some rocks that are possibly younger, including the Inda Ad Series. Evidence supports the assumption of at least two periods of metamorphism and folding, and some data suggest that the later episode was basically of stress metamorphism. Hunt (1958) suggested numerous metamorphic phases.

Authors consulted generally referred the basement rocks to the Archean, but with the changing usage of this term it is difficult to know what is implied. Several authors, however, considered the Somaliland rocks to be younger than the older basement rocks of central and east Africa and this is supported by recent age determinations on rocks of the former Somaliland Pro-

tectorate (N. J. Snelling, written commun., 1964) which suggest that these are to be regarded as later Precambrian.

The necessarily generalized interpretation given here discloses points of striking similarity between the basement rocks of former Somaliland Protectorate and those of Aden Protectorate. This similarity is reinforced by more specific observations.

Mason and Warden (1956) in their report on an area in the Erigavo District recorded plagioclase amphibolites in the older basement rocks, indicating intrusion of mafic igneous rocks into sedimentary rocks prior to metamorphism. Metasomatic granite is reported. Dioritic rocks containing xenoliths of metasedimentary rocks appear to have been intruded at a later stage in the history of the older basement development (see intertectonic intrusions of W.A.P., p. C29).

In a report on the Las Dureh area of the Burao District, Gellatly (1960 abstract) stated that basement rocks consist of a series of psammitic, pelitic, and calcareous sedimentary and associated volcanic rocks, which have undergone metamorphism varying from the greenschist facies to the granulite facies, with accompanying folding, metasomatism, and synorogenic granite emplacement. Both plutonic and hypabyssal mafic intrusive rocks are present. At least two periods of folding separated by a period of thrusting are recognized in the basement rocks.

Concerning the Inda Ad Series, Mason and Warden (1956) suggested that this rests unconformably upon the basement complex, and they referred to conglomerates at the base of the Inda Ad succession. The presence of a strictly basal conglomerate has been questioned by Greenwood (1960, 1961) who discusses alternative relationships between the Inda Ad Series and other basement rocks. Recent work on Somaliland rocks by Snelling of the O.G.S. Age Determination Unit tends to support a younger age for the Inda Ad Series, relative to that for the basement complex. No firm conclusions regarding the age relations of these rock groups are reached by Snelling, and all that can be said is that a simple interpretation of available results, leaving aside complicating factors, suggests metamorphism of the basement complex before 602 m.y. and deposition and dynamic metamorphism of the Inda Ad Series before 502 m.y. It cannot be concluded that the dynamic metamorphism of the Inda Ad Series was necessarily later than the most recent phase of metamorphism of the basement complex.

Taking into account the absence of polymetamorphic effects in the Inda Ad Series and the similarity of these rocks to latest Precambrian rocks of the Arabian Peninsula, the balance of recent evidence suggests

that the Inda Ad Series is younger than the basement complex of former Somaliland Protectorate.

The equivalence of the older basement rocks (basement complex) of former Somaliland Protectorate to the basement rocks of Aden Protectorate is indicated in the preceding review. On the basis of lithology, type and grade of metamorphism, and relation to other (older) basement rocks, the Inda Ad Series is tentatively correlated by the authors with the Ghabar Group of E.A.P. A number of posttectonic granite intrusions in both Somaliland and Aden Protectorate appear, on the basis of age determination results, to have a comparable early Paleozoic age. (See p. C93.)

SUMMARY

The suggested correlation between basement and certain other rock groups of regions of Arabia and bordering territories is summarized in table 4. This has been prepared from a review of relevant literature and from personal observations in Aden and former Somaliland Protectorate. The correlations shown are tentative and approximate only.

It is likely that basement rocks exposed in eastern Egypt, Jordan, Saudi Arabia, Yemen, Aden Protectorate, and former Somaliland Protectorate, and possibly also in Sudan and Eritrea, represent an upper Precambrian section of the African basement complex formed on the margin of the greater African Shield. The original sediments of the lesser Arabo-Nubian Shield were deposited in one or more extensive geosynclines. During later Precambrian times, events in the region seem to have followed the usual sequence of evolution of an orogenic belt. Sedimentation and igneous activity including vulcanism were followed by compression, regional metamorphism, granitization, and migmatization. Uplift of the compressed zone alternated with periods of stillstand during which igneous intrusive activity in some regions coincided with extrusive activity elsewhere. The history of sedimentation and extrusive activity indicates oscillations of level throughout later Precambrian times.

Marked shallowing or emergence, which occurred at some time near the end of the Precambrian, is indicated by unconformities, associated with conglomerates or boulder beds, beneath the Fatima Series of Saudi Arabia and its equivalents elsewhere. Unconformities are not proved in all regions, and it is probable that Fatima Series and equivalents were deposited in relatively local basins formed on the uplifted older basement rocks and that shallowing to the point of emergence was attained in some regions but not in others. Sedimentary rocks were derived from the exposed older basement rocks.

A later phase of renewed orogenic compression, of diminished severity, caused folding of the latest Precambrian rocks and imposed cleavage and a varying, but generally slight, degree of metamorphism. This phase marked the last incidence of orogenic folding recorded in rocks of the region. There followed epirogenic uplift which has continued, with alternating periods of stability and rejuvenation, until Recent times.

ADEN TRAP SERIES

The term "Trap Series" is applied to volcanic rocks occurring exclusively in the southwestern part of the Protectorate, which are considered to be of Late Cretaceous or early Tertiary age and are distinguished from later rocks of the Aden Volcanic Series. The Aden Trap Series corresponds, at least in part, to the volcanic rocks in Yemen referred to by Geukens (1960) as "Trappserie."

The Aden Trap Series crops out over a total area of about 1,400 square miles, in two main regions, namely:

1. To the north and northwest of Al 'Anad, extending to the Yemen border (and beyond) between Sanāb (north of Ad Dālī) and Al Kirsh.
2. To the north and northwest of Jabal Kharaz, again extending to the Yemen border.

Between these two regions of volcanic rocks, basement rocks are exposed. The eastern area of volcanic rocks is separated from basement rocks to the east by a zone of faulting running roughly northwest to north-northwest, east of a line between Ad Dālī and Al 'Anad.

The rocks consist of a thick series of dominantly basaltic lavas, with andesitic, trachytic, and rhyolitic representatives. Interbedded with these are tuffs, agglomeratic beds, and ash. The stratified series is cut by numerous dikes of composition similar to that of the lavas; many of these are porphyritic, and, in contrast with most dikes of basement-rock areas to the east, are unmetamorphosed. Dikes of granitic composition in the volcanic rocks are associated with intrusive granite. Sills of mainly doleritic composition are common, and certain possible laccolitic bodies of similar type are recorded, for example, on the Yemen border, north-northwest of Ash Shaṭṭ. The dikes and sills are of variable thickness; many of those seen were between 6 and 9 feet thick. They cut not only volcanic rocks but also Jurassic and Cretaceous strata.

The thickness of the volcanic series has been estimated from aerial photographs by the use of a parallax bar. At Ad Dubiyat some 7 miles south of Ab Dālī, quasi-horizontal volcanic strata exceed 2,600 feet in thickness; in the Ad Dālī area a thickness of more than 3,000 feet is estimated. These figures must be regarded

as very approximate, and the maximum thickness of the volcanic rocks may well exceed 3,500 feet. In many areas thicknesses cannot be estimated because of repetition by strike faults.

Where undisturbed by faulting the stratiform volcanic rocks are quasi-horizontal. The rocks are, however, much affected by faults, mainly trending approximately northwest, which produce tilted blocks in which the rocks dip at moderate angles to the northeast or southwest; the resulting terrain is in the form of a series of subparallel ridges. This strike faulting is indicated on aerial photographs by the fact that flows of differing composition (and hence of differing weathering resistance) and of differing tone are thrown into juxtaposition. Numerous faultline scarps are produced. Cross faults, generally minor, disrupt the continuity of the ridges.

DISTRIBUTION OF ROCK TYPES

During the course of the survey, a general tendency was noted for lavas of mafic type to underlie those of more silicic composition. This also appears to be so in comparable rocks of Ethiopia, where Lamare (1930) cited Blanford as distinguishing a lower group of basalts and dolerites and an upper group of trachytes(?), considered by Lamare to be rhyolites. In Aden Protectorate this twofold division is confused by the presence of mafic layers in the more silicic rocks. Many of the mafic layers are thought to represent sills.

Volcanic rocks in the Al'Anad locality include olivine basalts, rhyolites, tuffs, and agglomerate, with doleritic-basaltic sills and dikes; porphyritic dike rocks occur. A traverse by road from Al 'Anad to Ad Dāli, and northward to Sanāb on the Yemen border, shows that the volcanic rocks are predominantly of basaltic lavas, in which olivine and amygdaloidal calcite are conspicuous. Lavas are interbedded with agglomerates and red ash. The stratiform appearance is accentuated by the presence of doleritic sills which forms resistant layers in lava.

In the Al Musaymir area, basaltic rocks are again predominant, but representatives of trachytic lava occur.

In Wādī Timnān, above Ash Shaṭṭ, olivine basalt is interbedded with tuff and cut by dikes of silicic porphyry and dolerite. Near the Yemen border, north-northwest of Ash Shaṭṭ, banded rhyolites are common.

Aerial photographs of volcanic rocks exposed in Wādī Tarbābah for some miles above Ghayl Barbar, in the most western region of the Protectorate, indicate mainly intermediate to silicic rocks, which form dissected ridges in which fault-tilted flows strike northwest and north-northwest and dip in a general southwest direction. Field observations confirm this. A section immediately

to the west of the wadi at Ghayl Barbar shows, in descending order:

	Thickness (feet)
Capping of massive dense red cherty lava (rhyolitic)....	90
Shaly-weathering yellow-green tuff.....	120
Rhyolite.....	3
Vesicular basalt-andesite.....	20
Rhyolite.....	120
Yellow-green tuff.....	10
Gray weathered trachytic lava.....	3
Base of section not exposed.	

The lavas have a stratiform appearance resulting from flow layers generally 6-8 inches thick. Mafic and intermediate dikes cut these rocks.

The dominance of silicic volcanic rocks in the Ghayl Barbar area suggests that younger rocks of the series are here exposed.

MORPHOLOGICAL EXPRESSION

The volcanic rocks form rough terrain dominated by ridges trending northwest, formed from tilted elongate fault blocks of relatively restricted width. This type of terrain is interspersed with outcrops of nearly horizontal stratiform rocks, the tabular expression of which is emphasized by resistant layers of massive basaltic lava or doleritic sills interlayered with more easily weathering vesicular lava. Tuff and ash interbedded with lavas form multicolored, shaly-weathering horizons which also add to the stratiform appearance of the rocks. In several areas, striking tiered buttelike masses consist mainly of massive basalt, many with well-developed columnar jointing. Above and below Al Musaymir, plateau terraces of boulders and clay, spread with volcanic pebbles, are deeply dissected by the Wādī Tuban and its tributaries. In several areas, such as near Ad Dāli, cultivable soils are formed on the volcanic rocks. Such flat areas are broken by dikes of the volcanic series.

Dikes of mafic and silicic composition are very numerous and impart a ribbed appearance to the country, being generally more resistant than the extrusive and pyroclastic rocks. This is well seen in the Al 'Anad area. Most resistant are dikes of porphyritic type. In the Cretaceous sandstone of the 'Awābil area, as elsewhere, dolerite dikes form reduced negative features.

The rugged nature of the volcanic terrain is accentuated by the occurrence of spinelike volcanic necks and vents.

PETROGRAPHY

The petrographic characteristics of the Aden Trap Series and associated dike rocks are illustrated in the following examples.

Dominant among the lavas are basalts bearing olivine and including calcite forming amygdaloidal fillings.

These basalts may occur as massive rocks or as stratiform flows of little thickness. Specimen A20, from 4 miles north of Ad Dali', is an unmetamorphosed olivine basalt with partly serpentinized microphenocrysts of olivine in a granular groundmass of pyroxene, plagioclase, and iron ore.

A dike rock of ophitic olivine microgabbro or basalt, 1 mile north of Ad Dali', shows plates of augite, 2-3 mm in length, which enclose turbid plagioclase laths and are associated with serpentinous pseudomorphs after olivine. Radiating aggregates of fibrous zeolite have replaced part of the rock (A19).

In the Al Anad area a dike of porphyritic basalt cuts Cretaceous sandstone. This rock (A2) shows phenocrysts of labradorite in a groundmass of calcic plagioclase, clinopyroxene, biotite, and iron oxide minerals. Phenocrysts average 5 mm in diameter.

Andesitic rocks are represented by A47b, which is an altered quartz-andesite from a dike of Wadi Jadin, north-northeast of Jabal Kharaz. Abundant plagioclase laths occur in a turpid groundmass of brown glass, quartz, iron oxide minerals, and flakes of mica. Plates of a carbonate mineral and quartz appear to be secondary. Andesitic dike rock is also recorded from Ghayl Barbar.

Trachyte from the roadcut $2\frac{1}{2}$ miles southeast of Al Musaymir (A35) consists almost entirely of alkali feldspar in small laths in parallel orientation. Scattered patches of carbonate and minute octahedra of magnetite occur. Elongate stringers of quartz lie parallel to the flow direction.

A dike about 6 miles north-northeast of Al 'Anad is composed of porphyritic flow-banded glassy trachyte, in which rhomb-shaped phenocrysts of alkali feldspar, 2 mm in diameter, are commonly zoned and have cores of altered plagioclase (A12).

Dacite-porphry dike rock from Wadi Jadin (A47a) shows rhomb-shaped phenocrysts of albitized plagioclase 2-3 mm in diameter in a holocrystalline groundmass of quartz and plagioclase.

Spherulitic rhyolite from Al 'Anad (A1) shows spherulitic masses of epidote and granophyric "fans," as much as 7 mm in diameter, in very fine grained granophyric material.

Vitric tuff from the Ghayl Barbar section, noted above, consists of crystals of quartz and feldspar, with fragments of earlier pumice, in a pumiceous matrix containing abundant glassy shards (A56). A bedded crystal pumice-tuff with inclusions of volcanic glass (obsidian?), is recorded 3 miles west of Dar Rahban.

RELATIONS WITH ADJOINING ROCKS

It has been noted that volcanic rocks of the Aden Trap Series are separated from relatively elevated

basement rocks to the east by a fault zone east of the Ad Dali'-Al 'Anad line. Along this zone Jurassic and Cretaceous sandstone is preserved in faulted blocks, and the field relations indicate that the volcanic rocks are underlain by Cretaceous sandstone over the whole region. This accords also with observations in Yemen (Geukens, 1960).

In several localities—for example, northeast of Al Kirsh and northwest of Ash Shatt—Cretaceous rocks are associated with volcanic rocks over fairly limited areas, and this appears to be due to faulting along mainly northwest trends. In the west and southwest of 'Awabil, Cretaceous sandstone resting on basement rocks is cut by doleritic dikes of the Trap Series, and about 8 miles southwest of this center, volcanic rocks are thrown down against sandstone by strike faults, trending northwest, which result in complicated repetition of the rock types. Similarly, about 2 miles southeast of Al Musaymir, a tilted block of Cretaceous quartzitic sandstone, in which beds dip east-northeast, is displaced against volcanic rocks by a northwest-trending fault along the Al Musaymir road. Volcanic rocks on the northeast side of the road dip to the west-southwest. Further to the west-southwest of Al Musaymir, volcanic rocks rest upon Cretaceous sandstone, and both sedimentary and volcanic rocks are affected by faulting, resulting in tilted blocks in which dip is to the southwest.

Owing to the prevalence of this faulted relationship between Cretaceous sandstone and volcanic rocks, evidence as to their original relation is difficult to obtain. It is possible that volcanic rocks are interbedded with latest Cretaceous rocks, but data on this point are equivocal. Thus, about 12 miles southeast of Al Kirsh, on the southeastern margin of the Wadi al Kayfi basement rocks, a small outcrop of Cretaceous sandstone provides a section about 20 feet thick. This section shows an uppermost few feet of purple-white-mottled and baked-looking rock containing vitreous globules; this rock overlies a bed of red and white, discolored, and baked-looking sandstone, below which is volcanic rock, possibly trachytic. Similar sections exposed in the wadi show apparently altered and discolored sandstone beds between layers of volcanic rock. There was opportunity for only a very brief inspection of this occurrence, which may represent either Cretaceous sandstone altered by dikes of the Aden Trap Series (the strata dip, so inclined dikes might give rise to the section seen), or sandstone interbedded with volcanic layers.

A rather similar relation between volcanic rocks and Cretaceous sandstone was seen 8 miles north-northeast of Ash Shatt, near the Yemen border. Here sandstone and volcanic rocks form an apparently uniformly strati-

fied series dipping 45° in a direction of 220° . Quartzitic sandstone grades downward into 3 feet of altered purplish sandstone, which is followed by a 6-foot-thick dike of silicic porphyry above a 20-foot-thick sandstone horizon. Further unidentified volcanic rock underlies the sandstone. Petrographic examination of specimens of sandstone from near the contact with volcanic rocks shows the sandstone to be partly recrystallized. It is clear that at least some of the alteration of the sandstone is due to dike intrusion, but volcanic rock at the bottom of the series may represent lava. Faulting again largely obscures the stratigraphic relationships in this locality.

Aerial photographs of the Ash Shaṭṭ area show Cretaceous sandstone resting unconformably upon basement rocks and dipping about 15° SW. Strike faulting has resulted in a series of small cuestas with volcanic rocks covering lower slopes and valley bottoms. It appears that volcanic layers may be interbedded with Cretaceous sedimentary rocks but it is difficult to verify that this appearance does not result from repeated faulting. Sandstone and volcanic rocks are cut by numerous dikes which in this locality are steeply inclined nearly at right angles to the dip of the sediments.

In summary, field observations show that volcanic rocks are underlain by the greater part of the Cretaceous sedimentary succession, but it is possible that volcanic rocks are interbedded with the uppermost Cretaceous strata.

Some 5 miles to the north-northeast of Al 'Anad, Jurassic fossiliferous limestone is overlain by Cretaceous sandstone, the beds striking northwest and dipping at about 20° SW. The sedimentary rocks are separated from dominantly basaltic downdropped volcanic rocks to the northeast by a normal strike fault. To the southwest, volcanic rocks overlie Cretaceous sandstones. In the locality of Jabal al Munif intrusive granite, at least in part of peralkaline riebeckitic type, appears to postdate both sedimentary and volcanic rocks. This conclusion is based on field observations and the study of aerial photographs. To the south-southeast of Jabal al Munif, apophyses and bands of granite are invasive into volcanic rocks, and numerous granitic dikes extend into and cut the volcanic rocks. The Jurassic limestone at a locality about $1\frac{1}{2}$ miles north-northwest of Jabal al Munif is similarly penetrated by a band of granitic rock, and contact metamorphic effects are recognized. In the area to the south and southwest of Jabal al Munif, granitic bands, between 15 and 60 feet thick, alternate with volcanic rock. Many of the silicic bands are of light-colored microgranite. The whole assemblage is cut by later mafic and silicic dikes.

The alkaline granite of Jabal al Munif is distinguished from earlier granite exposed to the west of the Al Musaymr road some 2-3 miles northwest of Al 'Anad. Here Cretaceous sandstone rests upon the granite.

AGE AND ORIGIN

On the evidence available from the W.A.P., it is clear that volcanic rocks of the Trap Series are younger than the bulk of the Cretaceous sedimentary rocks of Nubian type. In Yemen, rocks of the basaltic trap series were stated to form interbedded layers in Cretaceous strata in the Southern (and Western) Highland rim (Rathjens in Wissmann and others, 1942). It is possible, therefore, that this is also true in W.A.P., where numerous dikes associated with the Aden Trap Series cut Cretaceous beds. In Yemen, Geukens (1960) recorded deposits interstratified with trap rocks, some of which yield freshwater fossils of Tertiary age. No Tertiary deposits other than late terrace deposits are known in W.A.P., but it is very probable that the bulk of the Aden Trap Series is of early Tertiary (Paleocene?) age. In summary, the Aden Trap Series is tentatively regarded as of Late Cretaceous to early Tertiary age. The alkaline granite of Jabal al Munif, intrusive into volcanic rocks, is considered to be of Tertiary age.

Aerial photographs of the Aden Trap Series show ash cones and volcanic vents in several areas, for example, between Al 'Anad and Ad Dā'il. These have also been seen in Yemen. In degree of weathering and reduction, the vents and cones contrast with the fresher and more clearly marked ash cones and craters of the later Aden Volcanic Series. In Yemen Wissmann (in Wissmann and others, 1942) recorded eruption fissures, many of which are aligned along directions parallel to the Red Sea axis. In W.A.P., many of the dikes in the volcanic rocks follow this direction, and some are apparently intruded along fault planes. Thus, eruption fissures may also have followed similar fracture planes.

GENERAL COMMENTARY

The Aden Trap Series exposed in the most western region of the Aden Protectorate is part of an extensive elongate outcrop of volcanic rocks associated with the Red Sea and Abyssinian rifts. Evidence from the Aden Protectorate and from neighboring regions suggests that this mainly Tertiary vulcanism was initially expressed in dominantly mafic basaltic lavas; subsequently the effusives became more silicic; trachytic and rhyolitic flows resulted, with obsidian and rhyolitic obsidian, and interbedded tuff, as exemplified in the Ghayl Barbar area of Aden. Basaltic rocks are not, however, entirely absent in this assemblage.

It is reasonable to suppose that the alkaline granite intrusive at Jabal al Munif, Al 'Anad, which appears to

cut dominantly basaltic volcanic rocks, was emplaced during this same phase of intermediate to silicic vulcanism. As noted, granites of apparently comparable age (Eocene?) have been reported in Yemen (Geukens, 1960); and in a postscript to his contribution Lamare (1930) recorded that petrographic examination of rocks from the area between Al Hudaydah and San'a', Yemen, revealed sodic granite and sodic microgranite.

Following the phase of silicic effusion there occurred a period of dike intrusion; the majority of the dikes are of doleritic and basaltic composition. Dikes (of this phase?) cut the alkali granite at Jabal al Munif, and it may be that they are of later Tertiary age.

Although the volcanic rocks of the later Aden Volcanic Series are in appearance and in topographical relations clearly distinguishable from the trap series, they seem to be magmatically part of a continuous series. The rhyolitic and trachytic rocks exposed in Aden Colony, which seem to have preceded the basaltic flows, may represent a continuation of the phase of silicic vulcanism of the trap series. Thus there seems to have occurred a cycle of effusions commencing and ending with dominantly mafic magma.

The evidence from Aden Protectorate and neighboring regions points to an alkalic olivine basalt association. Olivine basalts with alkalic affinities are known from continental areas, including the east African rifts, but in Aden Protectorate phonolites have not been recognized. The conditions which tend to be characteristic of the alkalic olivine basalt association, that is, crustal stability and faulting rather than folding or orogeny, are satisfied in the Aden region. But tholeiitic basalts are also characteristically found in a nonorogenic continental environment, and the quasi-horizontal extensive flows of Aden might well be identified with plateau or flood basalts. Against this, however, it must be recalled that evidence for other than fissure eruptions has been found and that regional flooding of alkalic basalt is known in Palestine and Syria.

In summary, such evidence as is available favors the assumption of an alkalic olivine basalt association.

The dominance of olivine basalts in volcanic provinces argues a magma of corresponding type as the parent of derived rocks. This opinion may be said to be currently orthodox. A process of magmatic differentiation involving fractional crystallization is also strongly supported.

The association of vulcanicity with the east African rift system, with the west Arabian (Red Sea) and Levantine rifts, and with rifting in other regions is well known. Although volcanic rocks are absent in certain stretches, such as Lake Tanganyika, and the degree of development is generally variable in other parts of the

rifts, the causal relationship is clear. The mechanism of rifting, connected with the basin-and-swell structure of Africa as a whole (Dixey, 1956a) is the subject of much discussion, but there is a large measure of agreement that the linear tectonic features involved (geosutures) are of great (primordial) age and great depth. These extensive fracture zones were subject to a recrudescence of activity at intervals throughout geological time.

Activation of the Red Sea-Ethiopian rift zone may have been accompanied in the early stages by eruption of basalt of deep-seated simatic origin. This suggests activity along the fracture zone in at least early Tertiary times. This dominantly basaltic effusion preceded further movement along the rift zone, for rocks of the Aden Trap Series were affected by faulting mainly of northwest trend. Girdler (1958), basing his opinions on gravity data, suggested that the intrusion of basaltic material into a crack along the present center line of the Red Sea caused subsurface movements which originated rift faulting along the margins of the sea, and that formation of the (present) wide fault trough is a collapse effect ultimately due to movement of igneous material into the fissure. He noted that stratigraphical work in east Africa has shown that rift faulting has repeatedly terminated periods of volcanic extrusion; he included tensional effects in his account of possible mechanisms.

It is possible that at a later date subsidence contributory to the formation of the Red Sea trough lowered crustal material to anatectic zones, and that this, combined in some way with magmatic differentiation, resulted in the eruption of alkali-rich volcanic and granitic rock. Thus it may be that the alkali granite exposed at Al 'Anad and elsewhere does not form part of a continuous granite series, but may be derived from a relatively shallow magma basin. Eruption of this alkali-rich phase may be of later Tertiary (Oligocene?) age.

DIKE ROCKS

Dike rocks of three main classes are recognized in the Protectorate, namely:

1. Dikes cutting basement rocks up to and including the intertectonic igneous rocks. Dikes of this class show a moderate degree of metamorphism of mainly dynamic type. They were not involved in the main period of regional (dynamothermal) metamorphism. Their age is considered to be later Precambrian.
2. Dikes showing no sign of deformation, which are therefore considered to postdate the widespread phase of dynamic metamorphism of late Precambrian date. Dikes of this class cut metasedi-

mentary rocks of Wādī al Ghabar and posttectonic plutonic intrusions, but they are not known to cut Jurassic or later rocks. Their age is tentatively regarded as early Paleozoic.

3. Dikes associated with the Aden Trap Series in the southwest of the Protectorate. These are unmetamorphosed. They may cut Jurassic and Cretaceous sedimentary rocks, and lavas and pyroclastic rocks of the trap series. They do not cut postlower Miocene basalts. They are referred to as post-Jurassic dikes.

PRECAMBRIAN DIKES

Precambrian dikes cut rocks of the Aden Metamorphic Group and associated syntectonic granites in many localities, for example, east of 'Awābil and in Wādī Raybān, Wādī Ḥḥwar, and Wādī Gharish. Dikes of this class are particularly numerous in the Mukayrās-Khawrah region where they mainly post-date mafic and granitic intrusions of the intertectonic group; in several places they show chilled margins against the granite. Andesitic dikes of the Mukayrās pass contain inclusions of intertectonic dioritic rock.

The obvious association of numerous dikes with the plutonic intrusions of the Mukayrās-Khawrah area, where both plutonic and hypabyssal rocks show conspicuous deformation effects, suggests a marked phase of dike formation following intertectonic plutonic intrusion. The presence of partly digested andesitic dike-like bodies in the Mukayrās granite, which form interrupted traces along a uniform strike direction in the granite, may suggest a phase of dike intrusion that followed mafic plutonic intrusion but preceded granite intrusion. In general, dike intrusion probably occurred intermittently in Precambrian times. Only those rocks subsequent to the main regional metamorphism were recognized as dike rocks in the authors' rapid reconnaissance. Many of the aplitic and microgranite dikes are thought to be associated with phases of granitic invasion.

Precambrian dikes comprise varied lithological types including basalt, dolerite, andesite and andesite porphyry, mafic lamprophyre, quartz porphyry, porphyritic granophyre, and felsite.

The thickness of the dikes ranges from 3 to 150 feet; a 150-foot-thick doleritic dike cuts granite some 12 miles north-northeast of Mukayrās. Data on strike trends are given under "Structure." Dikes of pegmatite and feldspathic rocks are referred to under "Granitic rocks."

The petrography of representative dike rocks is illustrated in the following examples.

A specimen of altered dolerite from the Mukayrās locality (A102) is composed of augite, calcic plagioclase,

and large plates of iron oxide minerals. Augite is partly replaced by green fibrous amphibole transitional to chlorite, and plagioclase is epidotized. The ophitic relationship between augite and plagioclase laths is clearly seen. Evidence of stress is provided by bent pyroxenes. The rock appears to have been subjected to incipient greenschist metamorphism.

A dike of altered gabbro from Thirah (Lawdar) similarly shows incipient transition to a greenschist assemblage. The original ophitic texture is partly preserved, but pyroxene is converted to actinolitic amphibole, and plagioclase is albitized (A96).

A specimen of altered porphyritic granophyre from a dike 3 miles north of Mukayrās (A104) shows phenocrysts of perthitic potassic feldspar, as much as 5 mm long, and phenocrysts of epidotized plagioclase in a groundmass of feldspar, quartz, epidote, and chlorite. Quartz is full of shatter cracks. The groundmass may possibly be recrystallized.

In the Khawrah district silicic and mafic dikes showing moderate metamorphism include altered dolerite and granophyric microadamellite.

A dike cutting schists of Wādī Gharish is composed of slightly deformed unaltered dolerite or microgabbro, and contains basic plagioclase laths as much as 4 mm long. Much of the pyroxene is converted to uraltite showing deformation effects and passing marginally to actinolite. Deformation is also seen in slightly bent feldspars.

LOWER PALEOZOIC(?) DIKES

Dikes of dolerite, aplite, and microgranite which cut metasedimentary rocks of Wādī al Ghabar and posttectonic granites at Niṣāb, Ṣa'id, and Burūm show no sign of deformation, and where sedimentary rocks overlie granites cut by these dikes, the dikes do not penetrate the Jurassic and later rocks. Dikes of this class appear to represent the last phase of intrusive igneous activity in the eastern part of the Protectorate. They are clearly pre-Jurassic and their probable connection with the later phases of igneous intrusive activity leads to the suggestion of an early Paleozoic age. Posttectonic granites of several areas have been dated by radioactivity methods as being of this age.

POST-JURASSIC DIKES

Post-Jurassic dikes associated with the Aden Trap Series, are described on page C44. Dikes of this class have been recognized cutting basement rocks in Wādī Dār, southeast of Al Kirsh, where they trend west-northwest across basement foliation strike. It is possible that dikes of unmetamorphosed andesite and dolerite cutting metamorphosed basement rocks at Jabal ath Thautyah may also be of this class. In

general, however, post-Jurassic dikes appear to be restricted to the southwestern part of the Protectorate, where they are commonly seen to cut Cretaceous sandstone, as at 'Awābil. Dikes of varied composition also cut the alkaline granite of Jabal al Munif, Al 'Anad, which is considered to be of Tertiary age.

SEDIMENTARY ROCKS

In the Western Protectorate, sedimentary rocks are mainly confined to an east-northeast- to east-trending belt, averaging 20 miles wide, between lines running northward from Aden and from Abwar: faulted sedimentary rocks mark the western margin of the main basement block, and restricted outliers occur at Al Mabfid and elsewhere in the basement-rock areas. Sedimentary rocks are also exposed in salt domes of the Ramlat as Sab'atayn.

JURASSIC

The oldest exposed sedimentary rocks are Jurassic in age and rest with well-marked unconformity on the weathered surface of the basement rocks. The sequence exposed includes the Upper Middle, and possibly Lower Jurassic, and was first named by Lamare (1930), as follows:

Upper Jurassic (Callovian to Ti-	
thonian).....	Amran Group
Middle to Lower Jurassic(?).....	Kohlman Formation

KOHLMAN FORMATION

The Kohlman Formation is lithologically rather uniform, comprising light-colored sands, sandstones, and marls together with pebbly and conglomeratic basal layers incorporating recognizable fragments of basement rocks. There is a gradational contact with the Upper Jurassic member, arenaceous beds passing through sandy limestones and gritty marls to limestones of Callovian to Oxfordian age. No fossils or plants have been reported from the Kohlman Formation either in the Yemen type section or in the Eastern Protectorate where the formation is more extensively exposed.

AMRAN GROUP

The Amran Group has been subdivided (Beydoun, 1960), as follows:

Coastal area	Salt domes
Naifa Formation.....	Naifa Formation
Madbi Formation.....	Sabatayn Formation
	Ayadh Member
	Layadim Member
	Shabwa Member
Shuqra Formation.....	Shuqra Formation(?) unexposed

The Amran Group is of variable facies and thickness, the latter due partly to erosion. In coastal areas it is a marine succession of limestones and marls, the neritic,

shallow-water facies of the Shuqra Formation passing upward into the more open sea deposits of the Madbi Formation and terminating again in shallow-water sandy beds of the Naifa Formation.

Inland, among Jurassic strata exposed in the various salt domes, the Shuqra is not seen but is presumed to be present, the lowest visible beds being evaporites of the Sabatayn Formation, which is considered to be equivalent to the coastal Madbi Formation.

The Naifa Formation is of similar facies throughout, in both coastal and inland sections, and represents the northward spread of open-sea conditions.

A section of the Shuqra Formation capping the basement rocks was examined at Al Maşānī, Abyan district; it consisted of about 230 feet of well-bedded gray limestones, veined with calcite, and thin marls.

Fossils identified by the British Museum (Natural History) included the following: *Gryphaea costellata* (Douvillie), *Ceratomya* sp. (possibly *C. wimmisensis* (Gillieron)), *Modiolus umbricatus* (J. Sowerby), *Brachydontes* (*Arcomtilus*) *laimairensis* (de Loriol), *Lima* (*Plagiostoma*) sp., *Limatulus* sp., *Sphaerioda*? sp. (possibly *S. madridi* (d'Archiac)), and *Globularia* cf. *G. chauriniana* (d'Orbigny). On the basis of *Gryphaea costellata*, the most useful species for correlation, a Bathonian or Callovian age is assigned to this assemblage.

Other specimens taken from Al Maşānī included: *Daghanirhynchia daghaniesis* Muir-Wood and varieties, *Bihenithyris barringtoni* Muir-Wood and varieties, and *Bihenithyris weiri* Muir-Wood. These species resemble the fauna, described in 1935 by Muir-Wood, from the former British Somaliland and are taken to be of Callovian age.

At Bilb, near Al 'Anad, a 230-foot section of well-bedded dark gray limestones and thin marls, capping a south-dipping basement block, yielded specimens of *Isastraea* sp. This is a well characterized species that appears to be new and to be allied to *I. kosodeensis* Eguchi from the Upper Jurassic limestone of Japan. According to the British Museum (Natural History) no definite age can be assigned to it, for the range of the genus is Middle Jurassic and Cretaceous, but a Late Jurassic age is probable. A more complete faunal assemblage from the Shuqra Formation has been described by Hudson (1954), from a locality near the town of Shuqra.

The Madbi Formation succeeds the Shuqra Formation and occurs in all Jurassic sections unaffected by erosion. It consists of a series of marls, many of which are gypsiferous, with scattered beds of gypsum, and thin rubbly fossiliferous limestones. Its lower contact may be locally disconformable as in Wādī Gharish (Beydoun, 1960) but the upper contact is conformable

and locally gradational. From the fossil evidence, a Kimeridgian age is indicated.

The Madbi Formation is considered to be equivalent to the Sabatayn Formation, as seen in the inland salt domes, on the basis of the evaporites, doubtful fossil evidence, and the presence in both areas of the overlying Naifa Formation; evidence from eastern Yemen also supports this (Geukens, 1960).

The Sabatayn Formation consists of an evaporite series with interbedded shales and gypsaceous marls, and, from the top down, has been subdivided (Beydoun, 1960) into the Ayadh (M'qah), Layadim, and Shabwa Members. The base is not exposed. Between 265 and 920 feet of the various members is exposed in the salt domes which occur in the 'Iyadh area of Hayd al Milh (lat 15°05' N., long 46°49' E.), in the Shabwah area (lat 15°22' N., long 46°49' E.), at Shabwah itself, Milh Kharwah, and Milh Maq'ah. In the Ramlat as Sabatayn about 40 miles northeast of Bayḥān is the Layadim dome.

The Shabwa Member crops out in all the salt domes; its base is not exposed and it reaches 100 feet in thickness at 'Iyadh. It is composed of gray, laminated shale, in places folded and contorted, with inclusions of gypsum and marly materials. That it is conformable with the overlying member demonstrates the depositional nature of the salt.

The Layadim Member consists of bituminous black paper shales with bands and veins of marl and salt. At the Layadim dome, massive salt is overlain by varicolored shales, bituminous in part, and gypsiferous beds. Toward the crest of the dome, salt is interbedded with fragments and blocks of contorted gray paper shales having thin lignite bands. Well-formed salt crystals are found lining fractures in brecciated shale and as stalactitic deposits under cliff faces, and in vugs. In the Shabwa dome, abundant *estheria* and *spongistroma*, together with the fish *Anaethalio*, suggest a Late Jurassic age for this member.

The Ayadh Member consists of marly and bituminous limestone with limestone and interbedded gypsum. It rests unconformably on the Layadim Member and is of variable lithology and thickness, reaching 750 feet at 'Iyadh; it grades laterally into the M'qah Member, which is developed at the Milh Maq'ah dome as about 500 feet of coarse green ripple-marked sandstone containing plant remains, shaly limestone, and gypsum.

The Naifa Formation, as seen in the 'Iyadh salt dome, consists of thin-bedded porcellaneous limestones with platy dolomites and marly layers. It is apparently conformable with the underlying Ayadh Member. At 'Iyadh one ammonite, *Barriesella* sp., of probable Thithonian age has been recorded. At other salt domes the Naifa Formation has been removed by erosion.

At Sāfir, on the eastern border of Yemen about 12 miles southwest of Jabal al-Thaniyah, a salt dome has been described by Geukens (1960). As in the Layadim dome, the salt is folded and contorted; it is flanked by bituminous and marly shales which yielded pollen and spores of *Classopollis reclusus* (Theigart), *Ephadra strobilacea*, *Gleichenioidites feronensis* (Delcourt and Sprumont), *Monosulcites* sp., and *Inaperturopollenites* sp., of Late Jurassic age. Those beds are succeeded by about 160 feet of gypsaceous shales, sandy shales, and limestones. The arenaceous and gypsaceous beds may be correlated with the M'qah Member; the salt and bituminous shales correspond to the Shabwa and Layadim Members of the Sabatayn Formation. This confirms the western extension of the basin in which the evaporite rocks of the Sabatayn Formation were deposited.

REGIONAL CORRELATION

In Yemen, Geukens (1960) described an unfossiliferous fluviolacustrine and deltaic series, that occurs between the eroded surface of the basement rocks and the upper fossiliferous Jurassic beds, and correlated it with the Kohlan Series as named and described by Lamare (1930). Overlying the Kohlan Series or resting directly on the basement rocks is a fossiliferous series of well-bedded limestone, with thin shales and marls, whose faunal assemblage is of Callovian to Oxfordian age; this series was mapped by Geukens (1960) and was correlated with the Amran Group of Lamare.

A series of transitional beds which are variable in lithology and thickness overlie the Amran Group, as noted by Geukens. In some localities the beds are absent, and Cretaceous sandstones rest directly on the basement rocks. In southwest Yemen the transitional beds are 500 feet thick, consist of shales and gypsum, and elsewhere, as in the southeast, contain limestone and marl. On the basis of the gypsum content, a correlation was made by Beydoun (1960) with the Sabatayn Formation of the Aden Protectorate. Outside this evaporite basin, limestones of more open sea deposition were correlated with the Madbi Formation. No beds similar to the Naifa Formation are present in Yemen; thus, dry-land conditions or emergence in that area are indicated.

CRETACEOUS

Cretaceous beds are not extensively exposed in the Western Protectorate. In general, the beds vary in thickness and lithology from west to east and show several well-marked unconformities. They rest unconformably on Jurassic beds (fig. 17)—or directly upon basement rocks—the contact being marked by

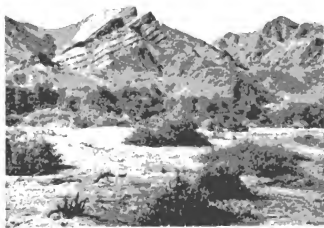


FIGURE 17.—Cretaceous sandstone overlying Jurassic limestone, Wādī Raybān.

a zone of conglomerate. They fall into two lithostratigraphic groups, subdivided and named by Beydoun (1960), as follows:

Age	Western Province		Eastern Province	
Senonian (probably Campanian-Maastrichtian)	Tawilah Group	Mukalla Formation	Makra Group	Sharwayn Formation
				Mukalla Formation
Cenomanian to Albian (probably including some Turonian)		Harshiyat Formation		Fataq Formation
				Harshiyat Formation
Aptian-Barremian		Qishn Formation		Qishn Formation
Jurassic beds or basement rocks				

The Tawilah Group is predominantly clastic with lenses of marl and limestone thickening eastward, whereas the Makra Group is mainly a limestone-marl facies with sandstone intercalations.

In the area under description, the Tawilah Group is a varicolored succession of ferruginous locally current-bedded sandstone, siltstone, marl, and shale, with much conglomerate. Scattered lenses of limestone contain a faunal assemblage of Barremian to Maestrichtian age.

The Qishn Formation is not distinguishable from the overlying clastic deposits on the borders of Eastern and Western Aden Protectorate, but is represented farther east by fossiliferous limestones and marls. The formation rests unconformably on various members of the Jurassic sequence which was disturbed by terminal Jurassic earth movements and eroded.

Overlying the Qishn conformably is the Harshiyat Formation of Albian to Cenomanian age. It is a

clastic series with predominating current-bedded sandstones, as well as marls and shales. Two fossiliferous marine limestone lenses occur in the east, the upper or Sufia Member separating the Harshiyat from the overlying but lithologically similar Mukalla Formation. The lower or Rays Member occurs within the basal clastic strata. Both these limestone members pinch out close to the 48° meridian.

The Mukalla Formation is of Senonian age and lies conformably at the top of the Tawilah Group east of 48° longitude, and is a varicolored sequence of clastic beds.

Regional correlation.—In Yemen the Taouilah Series described by Lamare (1930, 1936) was divided by Geukens into a lower or "Nubian" sandstone facies, of continental origin, and an upper Medj Zir Series, which is neritic and contains a Paleocene to Eocene fauna. In southwest Yemen the upper beds of the Taouilah Series contain trap lava sheets, demonstrating the commencement of volcanic activity contemporaneously with marine sedimentation of the Medj Zir Series in other areas.

TERTIARY

PALEOCENE TO MIDDLE EOCENE

The Paleocene epoch was marked by a widespread transgression which covered the greater part of Eastern Aden Protectorate and eastern Saudi Arabia while volcanic activity continued in Yemen and parts of Western Aden Protectorate.

A considerable thickness of calcarenites was laid down during this period, which ended with general uplift and emergence in the late Eocene time. This group of rocks, which includes some evaporite and clastic deposits has been named the Hadhrat Group by Beydoun (1960), and is present as a narrow strip west of the 48° meridian.

The group is subdivided as follows:

Emergence.....	Upper Eocene
Hadhrat Group:	
Habsbiya Formation.....	Middle Eocene
Rus Formation.....	Lower Eocene
Jaza Formation.....	Do.
Umm er Radhuma Formation.....	Paleocene
Transgression.	

The Umm er Radhuma has been shown on fossil evidence to rest disconformably on the Cretaceous beds (fig. 18). At the type locality in the Hadhrat it consists of a basal dolomite overlain by paper shales and nodular limestone, succeeded by a thick sequence of massive dark-brown and gray commonly dolomitic limestone which is distinctive in the field. Toward the top of the formation a thick zone of nodular shaly cavernous limestone forms cliffs, and slumped sections



FIGURE 18.—Paleocene limestone overlying Cretaceous sandstone, 6 miles north-northeast of Al Khabr.

are common. The formation thins out in a westerly direction toward a shoreline which is presumed to lie somewhere in the Western Protectorate. It is considered to be homotaxial with the trap lavas of Yemen and the Western Protectorate border areas.

The Jeza Formation overlies the Umm er Radhuma conformably and consists of paper shale, marl, and limestone, with chert and gypsum layers present toward the top.

The Rus Formation is typically developed in Saudi Arabia, and in the Aden Protectorate consists of massive gypsum, with limestone bands and marls. These cap many of the limestone plateaus and form a distinctive pattern on aerial photographs.

The Habshiya Formation is the top member of the group and occupies a very limited area north of Mayfa 'ah, in the region under description, and consists of yellow to pink paper shale, marl, and limestone, with a rich foraminiferal assemblage, as well as echinoids.

OLIGOCENE AND MIOCENE

The Shihr Group is a transgressive series laid down in coastal embayments and tectonic depressions after emergence of the land surface at the end of the Eocene Epoch. The group consists of limestone, marl, shale, and gypsum, and rests on a variety of older formations. The group is not represented west of 48° longitude.

POST-MIOCENE

Post-Miocene deposits appear as raised beaches of various elevations and ages, and occur extensively along the coasts of the Arabian Peninsula; inland they commonly pass into the river terraces.

Other late Tertiary to Recent deposits include alluvium, loess deposits, and probably the sand deserts, such as the Ramlat as Sab'atayn.

ADEN VOLCANIC SERIES

The term "Aden Volcanic Series" is derived from Blanford's (1869) description of the "Aden Series."

PREVIOUS WORK

McMahon (1883) gave petrological descriptions of Volcanic rocks collected from Aden. These included basalts, some vesicular, containing augite, porphyritic feldspar, and altered olivine; also andesites, trachytes, quartz trachytes, trachytic pitchstone, and pumice. McMahon noted that the inside of the main Aden crater presents an unbroken succession of lavas from silicic pitchstones to basaltic rocks. Silicic rocks seem to have predominated. McMahon was unable to give the order of succession of the mafic intermediate, and silicic lavas.

Raisin (1902) described rock specimens from Perim Island. All the specimens examined were volcanic. Those found in place included basalts and tuffs.

Lamare (1930), in his discussion of post-Cretaceous vulcanism of the Red Sea and neighboring countries, proposed a division into *eruptions anciennes*, prior to subsidence (of the rifts and fault troughs), and *eruptions recentes*. The latter correspond to the Aden Volcanic Series. Lamare noted that the grouping is not clear cut and that overlapping of the two types occurs. The following notes refer to the recent eruptions.

With reference to the northern border of the Gulf of Aden, Lamare mentioned puy's in the locality of Bāb al Mandab; he also mentioned Jabal Kharaz, said to attain a height of 839 m., Jabal Sunamina (168 m.), Jabal al Birkah (229 m.), and Jabal Marsā. No studies of these "volcanoes" were recorded. The Aden Volcano was considered to be older than the just-mentioned basaltic puy's, on the evidence of more advanced denudation. Petrographic studies by several workers between about 1874 and 1907, cited by Lamare (1930), indicated, from Aden and Little Aden, lavas of quartz-trachyte (liparite), rhyolite approaching pantellerite, comendite, and trachyte passing to andesite (trachyandesite). Quartz trachytes may contain riebeckite. Lamare remarked that these alkaline rocks form the base of the Aden Volcano and are succeeded by basaltic and doleritic flows. Brief mention was made of volcanic rocks in the Balhāf and Bi'r 'Alī areas of E.A.P., consisting of olivine basalt with basaltic cones of undoubted Quaternary age. A volcano in the interior of Ḥaḍramawt, Bir Barhūt, was referred to as being active at the end of the 10th century.

Jaques (1954) gave a brief description of volcanic rocks, believed to be of very recent age, occurring at Aden Peninsula, between Shuqrah and Aḥwar, and near Bi'r 'Alī. He recorded thin bands of lava cutting sands of the coastal plains at Shuqrah and in the sea off Little Aden. At Aden Colony the rocks were said to be mainly of ash and tuff, and only a relatively small amount of lava is of andesitic or trachytic composition. At Little Aden, lava was said to be more in evidence and of very variable type. Jaques was unable to determine the location of vents at Aden or Little Aden and regarded the crater locality of Aden as an unlikely spot for the center of volcanic activity.

Beydoun (1960) mentioned that volcanic cones and basalt sheets are found along the coast from Aden into southeast Ḥaḍramawt, and sporadically farther east. They are probably associated mainly with the Neogene to Recent coastal faulting.

Iring and Tarling (1961) gave some description of the Younger Volcanics of the Aden Peninsula which were sampled in connection with paleomagnetic studies. The Aden Volcano is said to consist of lava flows and pyroclastic rocks intruded by trachyte plugs. The

main crater is in the eastern part of the peninsula, the peak of Spion Kop being the central cone. The base of the volcanic rocks is not exposed. Their age is estimated as Pleistocene or Recent by reference to the extent of erosion and preservation of land forms. An earlier age is not excluded. In Holkat Bay (lat 12°46' N., long 45°02' E.) and Khushaf Valley (lat 12°46' N., long 45°01' E.), massive trachytes were sampled at eight sites. These may be plugs or possibly thick flows. An evidently intrusive trachyte plug was sampled in the Golden Mohur Bay area (lat 12°46' N., long 44°59' E.).

DISTRIBUTION

Rocks of the Aden Volcanic Series cover an aggregate area of approximately 1,600 square miles in W.A.P. and perhaps 120 square miles in E.A.P., to as far east as the longitude of Al Mukallā.

In the Western Protectorate, outcrops have been mapped as follows: At Perim Island in the Straits of Bāb al Mandab; in the locality of Jabal Kuwah, north-east of Ḥiṣn Murād; in the area of Jabal Kharaz; as small outcrops at Jabal al Birkah and Jabal Marsā; at Ra's 'Imrān; at Aden and Little Aden; between the coastal centers of Shuqrah and Aḥwar; and extending inland as far north as Aṣṣurrah.

These outcrops are mostly coastal. More restricted lava flows are distributed around volcanic centers farther inland in W.A.P. Some of these are of very small extent and are found in isolated remnant patches in wadis. The main occurrences are about 18 miles south of Niṣāb, where basaltic lava rests upon basement rocks; in Wādī Abadan, 4 miles south of Al Ḥujayrah; and northwest of 'Ataq, where isolated outcrops of basalt, roughly elongated in a northwest-southeast direction, extend about 25 miles. The well-developed extinct crater of Al Kirsh ('Ataq) is included in this group.

In E.A.P. the largest group occurs between the port of Balhāf and Bi'r 'Alī, extending inland to a maximum of about 12 miles. Further, smaller patches of basalt occur at Karif Shawrān, east of Bi'r 'Alī, and at Ra's Majdah and to the north of it. Basalt flows and cobble spreads are seen in the lower reaches of Wādī Ḥajr, in Wādī Raymah, and also in Wādī al Ghabar. Small outcrops have been identified to the north and northwest of Jizwil. In the area of Ra's Quṣay'ir, some 85 miles east-northeast of Al Mukallā, basalts appear from aerial photographs to rest upon Oligocene and Miocene Shihir beds, and flows follow valleys cut in these rocks. Aerial photographs show volcanic rocks of the Aden Series between Muṣayni'ah and Sharkhāt and inland from this coastal strip.

Aden Peninsula.—In the Aden Peninsula the volcanic rocks of Little Aden have not been examined other than on aerial photographs, which in certain localities show dark-toned (basaltic?) lava apparently overlying lighter toned (silicic?) lava.

The main feature at Aden is the extinct crater, breached (that is, denuded and reduced) on its eastern and northeastern side. The elevated rim on the southern and western circumference appears, from aerial photographs, to consist of thin beds of interstratified tuff, ash, and breccia. The quaquaversal dip of these beds, and of more peripheral lava flows which reach to the sea in many places, serves to confirm the identity of the crater. The center of the crater is floored by a dissected plateau of lava which is of trachytic type at some places, for example, in the locality of the ancient tanks, but which may possibly have a central plug of basalt.

The variety of volcanic rock types found at Aden is indicated by the data given in details of previous work. In addition, specimens taken from the northern slopes of Al Aineh include:

1. A fine-grained trachyte with phenocrysts of alkali feldspar set in a fine groundmass of alkali feldspar microlaths. Other feldspars show crosshatched twinning suggestive of anorthoclase. Granules of aegirine-augite and octahedra of magnetite are abundant. Some interstitial quartz and a carbonate mineral are present.
2. A silicic volcanic rock—trachyte(?) or rhyolite. In this rock microphenocrysts of alkali feldspar, finely twinned sodic plagioclase, and aegirine augite occur sporadically. The fine groundmass is nearly indeterminate but includes colorless glass with spherulitic texture, feldspar laths, and abundant altered sodic(?) amphibole.
3. A highly vesicular porphyritic basalt. Red pseudomorphs of iddingsite suggest original olivine. Clinopyroxene and plagioclase form the medium-grained groundmass.
4. A fine-grained basalt with plagioclase microphenocrysts. The groundmass is of calcic plagioclase, pyroxene, and magnetite. Scattered crystals of iron-strained olivine are rimmed by pyroxene.

Karīf Shaurān.—The well-preserved extinct crater of Karīf Shaurān is near the coast some 2½ miles east of Bi'r 'Ali, E.A.P. The landward lip of this crater reaches an elevation of about 300 feet above the general ground level. A saline crater lake, with a species of mangrove at the periphery, proved to have a water level corresponding to sea level, and local information indicated that tidal changes affect the lake, which must therefore be in communication with the sea. The

crater walls show quaquaversal dips and are composed of tuffaceous material and ash that have a calcareously cemented crust, fractured to a mosaic pattern. The inclination of the upper slopes was measured as 24°; that of the lower slopes, as 13°. Ejected material found on the side of the cone included pebbles of olivine basalt, syenitic rock, silicic lava, gabbro, and dunite of bottle-green glassy olivine. Other less well preserved craters and cones are present in the area.

General.—Apart from the mixed rocks of the Aden Peninsula, other exposures of the Aden Volcanic Series consist of basaltic flows and pyroclastic material. The lava appears to have erupted mainly, if not entirely, from central vents, the evidence for which is well shown in cones of ash and agglomerate, many of which appear fresh and well preserved. These occur between Shuqrah and Aḥwar, in the Balḥāf-Bi'r 'Ali area, and elsewhere.

The largest extent of basaltic rock is that of the Shuqrah-Aḥwar outcrop, where flows rest upon basement rocks or upon Jurassic and Cretaceous sedimentary rocks. The character of the basalts, here and elsewhere, varies from scoriceous vesicular ropy lava, mixed with pyroclastic material, to massive columnar-jointed rocks. Olivine is a nearly ubiquitous mineral component. At Jabal Kharaz massive dense basalt is interlayered with highly vesicular "thin-bedded" flows, weathered to a honeycomb rock.

Between Balḥāf and Bi'r 'Ali cones of red ash and cinders produce striking scenery, standing above plateau-forming lava flows (fig. 19). The flows in many places form steep-sided ridges, as though constrained to flow in channels cut in pyroclastic material or possibly alluvium, which has since been denuded. The elevation of bedrock underlying basalt in this area is not known, but it is probable that flows exceed 200 feet in thickness.

AGE

The comparatively recent age of the Aden Volcanic Series is attested by its appearance both in the field and on aerial photographs and by the topography. The flows are seen filling recent water courses and upon terraces. East of As Sawād on the Ar Rawdah road, basalt caps terrace conglomerates that rest upon Cretaceous sandstone. The Wādī Rufād, 11 miles north of Jil'ah, E.A.P., an estimated 40-50 feet of columnar basalt rests upon some 100 feet of terrace deposits consisting of beds of calcareous silty clay, 1-4 feet thick, interstratified with boulders (fig. 20). The state of preservation of many of the ash cones also indicates a very recent age for much of the basaltic rock, but aerial photographs of the area between Shuqrah and Aḥwar, as elsewhere, clearly show flows of differing age (fig. 21). Extrusion of lava was intermittent over a considerable period. Further evidence that basaltic flows are of



FIGURE 19.—Basalt flows and volcanic cones of the Aden Volcanic Series, north of Karif Shawrân, Bi'r 'Alî.



FIGURE 20.—Columnar basalt resting on terrace deposits, 11 miles north of Jil'ah.

differing age is the fact that no raised beaches are seen on the flows between Bi'r 'Alî and Bulhâf, whereas terraces are cut in basalt in Wâdî Hajr.

As noted above, basalts appear to pierce through and rest upon Oligocene and Miocene Shihir beds at Ra's Qusay'ir; in former Somaliland Protectorate basalts of the Aden Volcanic Series rest upon Miocene

Dubar Series (Greenwood, 1960). These volcanic rocks seem clearly to be post-early Miocene, and it is concluded that the Aden Volcanic Series is of late Miocene or Pliocene to Recent age.

There is reason to suggest that the more silicic phases of eruption seen in the Aden Peninsula preceded basaltic effusions. Further support for the later date of the basalts stems from the fact that all lava flows seen elsewhere in the Aden Volcanic Series, some of which are clearly of very recent date, are of basalt.

REGIONAL CORRELATION

Volcanic rocks equivalent to the Aden Volcanic Series have been recorded in Yemen as flows of varying age, and in the remains of extinct volcanoes (Geukens, 1960; Lamare, 1930). They have also been recorded in Ethiopia (Lamare, 1930). In former Somaliland Protectorate, the Somaliland Oil Exploration Company, Ltd. (1954) noted these rocks in the Bulhar area and in the western boundary region where basaltic flows extend from the coast along the border between former British and French Somaliland. The series is dominantly basaltic, but rhyolites and tuffs occur locally, mostly near, or forming, volcanic vents.

STRUCTURE

The Protectorate is broadly divisible into three, parts namely the sedimentary plateau of E.A.P., the tecton-



FIGURE 21.—Aden Volcanic Series, north of Shuqrah. Basaltic flows rest upon Jurassic limestone (1) or upon basement rocks (2). Flows of two stages are discernible (a and b). Royal Air Force photograph. Crown copyright reserved.

ically uplifted main basement block of W.A.P., and a structurally depressed area in the southwest mainly covered by volcanic rocks of the Aden Trap Series.

Basement rocks underwent at least two main periods of stress, with concomitant folding, metamorphism, and syntectonic granite invasion. Certainly since Mesozoic times and probably since the Early Cambrian, movements in the Gulf of Aden region have been of epeirogenic type. The Jurassic and later history is one of intermittent uplift and successive marine transgressions from an easterly direction. In Late Cretaceous and Paleocene times and again in late Miocene to Recent times, vulcanicity accompanied uplift and faulting. Eustatic movements from Pliocene times resulted in raised beaches and downcutting by wadis through thick terrace deposits.

BASEMENT STRUCTURE BASEMENT STRIKE TRENDS

The photogeological map prepared by Overseas Geological Surveys at a scale of 1:500,000 provided the first plot of basement strike trends in Western Aden Protectorate. These basement strike directions cannot be shown on the Arabian Peninsula geological map at the scale of 1:2,000,000, but they are indicated in a somewhat generalized form on plate 1. Some explanation is required to clarify the significance of the strike lines shown.

Fieldwork in Aden Protectorate has proved that, over a large part of the region, foliation (here used in a general sense to include schistosity and gneissose foliation) and flow cleavage are parallel with the axial planes of folds; as tight folding is very common, a general parallelism between relic bedding and foliation exists. Relic bedding can be clearly discerned in the field in many areas, so this expected parallelism can be confirmed. Numerous bands of resistant rock, such as crystalline limestone and quartzite, commonly of small thickness, facilitate the recognition of stratigraphic horizons from aerial photographs, and such marker beds are seen to strike concordantly with the foliation of other basement rocks. Thus over most of the region the lineations plotted from aerial photographs may fairly be regarded as representing the strike of both bedding and foliation. In places of significantly plunging structures, however, where marker beds are absent, it is not possible to know whether relic bedding or foliation is plotted. Also, fieldwork has shown that in some localities relic bedding is not coincident with foliation. In such places, it appears that, wherever this has been checked, foliation or cleavage is reflected in aerial photographs (and has therefore been plotted), rather than relic bedding.

In the southwestern part of the Protectorate, the overall strike trend of the basement rocks is approxi-

mately northeast, with a swing to north-northeast in the area of the headwaters of Wādī Banā, west of Mukayrās. This north-northeast direction is continued in the Bayḥān area, changing to north on the southern border of the Ramlat as Sab'atayn. In the main ridge of Jabal ath Thanyah the strike is also within a few degrees of north but changes to northwest in the northern appendage of this range.

The northeast trend seen in the southwestern region of the Protectorate continues through the Mukayrās-Lawdar area, where the escarpment of the Kawr al 'Awādhil forms a parallel feature, and extends along, and to the west of, Wādī Durā to about the latitude of Niṣāb.

To the northwest and east of Niṣāb, an abrupt change of strike occurs, the trend here being northwest. This break is marked by minor mapped faults, but the presence of a major fault running northwest through Niṣāb and linking with faults on this trend in the southeast sector of Jawl aṣ Ṣalab is suspected. The northwest strike trend is clearly expressed in a belt of steeply dipping rocks extending from near 'Ataq southeastward through As Sufāl to the 14th parallel. The strike of the basement rocks is here parallel with the major fault zone that separates basement rocks from sedimentary rocks to the east.

A strong east-west component is seen in the rather variable strike trend of the region bounded by Mūdiyyah to the west, by Niṣāb to the north, and by 'Irqah to the east. In the east and southeast of this region the strike swings through northeast to reach parallelism with the northwest fault zone mentioned previously.

In E.A.P. the foliated rocks flanking granite and the Jibāl al Aswad range show a west-northwest strike parallel with the elongation of the range. The basement rocks of the Wādī Gharīsh area, although variable in detail, maintain an overall strike of about 10° west of north. Metasedimentary rocks of Wādī al Ghabar strike between north and about north-northwest. By contrast, the elongate dome structure of Zūlm Bā Tha'lab (older volcanic rocks), and also the basement rocks at Jabal Jahnum, Wādī Ḥajr, trend roughly east-northeast.

Attention is drawn to the parallelism between the basement strike over extended areas and to the several directions of the regmatic shear pattern.

Distortion of the strike of basement rocks by plutonic intrusions is seen in the area to the south of Niṣāb, in the southwestern part of the Jibāl an Nisīyīm block, and in the Bayḥān area. In these localities the foliation strike curves around the granite margin and suggests the advent of granitic plutons as near-solid masses. In some places the disruptive effect upon foliation strike was minimized, where the intru-

sions formed bodies elongated parallel with the basement grain, as at Jibāl al Aswad, and on a smaller scale to the south of 'Ataq, where mafic plutonic rock caused slight divergence of basement strike. In contradistinction to the distortion of basement strike by later plutonic intrusions, the coincidence between foliation of granitized rock and adjoining basement rock is well seen on aerial photographs.

DIKE DIRECTIONS

Many of the dikes of varied composition and age, which cut basement rocks, follow northwest and northeast directions, as in the Mukayrās-Khawrah area. In volcanic rocks of the western part of the Protectorate the northwest direction appears dominant. Although definite evidence is not available in the absence of a statistical analysis of a large number of dike directions, observations suggest that these are the preferred orientations of the majority of dikes. The northeast direction is also followed by many but not all dikes and veins of pegmatite, quartz, and feldspar.

Other main directions followed by dikes include north-northwest, north-northeast, and west-northwest. Dikes trending north and east also occur, and it may be significant that these appear to be the preferred directions of dikes cutting later granites.

JOINT DIRECTIONS

Joint directions in granitic rocks are similar to those noted for dike intrusion, with the additional east-northeast trend seen in the Sa'id granite. Major north- and east-trending joints were seen in granitic rocks of Mukayrās, Mūdiyyah, Niṣāb, Jibāl an Nisīyīn, and Jibāl al Aswad.

Apart from fracture cleavage, which affects basement rocks of all areas, more widely spaced fracture planes approximately at right angles to foliation are also common.

MAJOR FOLD STRUCTURES

The study of aerial photographs of the basement rocks of the Protectorate shows that these have undergone intense and complicated folding and contortion, the unravelling of which would entail much detailed work. In the reconnaissance of a large region this could not be done, and it is possible only to point out some of the more obvious structural effects, and to note the opportunity for further work in this territory.

A fold structure of considerable significance occurs some 10 miles west of Yashbun near the eastern margin of the main basement-rock area, which is delimited by a major zone of faulting trending northwest. This is an asymmetrical synclinal fold or synclorium in which the rocks forming the limbs are involved in subsidiary close folds. The structure has a curving

axis which, in the northern, more clearly defined part, plunges to the south-southwest. The northern continuation of this structure is obliterated by the invasion of granitic rock but the attitude of the exposed structure suggests that the axis of folding continued to swing through a north direction to become parallel with the fault zone to the east. Steeply dipping rocks of the east flank strike parallel with the fault zone, and the general disposition of the fold suggests reorientation of an original east strike by compressive stress transmitted through sinistral transcurrent movement along the fault zone referred to. This is supported by conditions to the south of the synclinal area where, near Al Maḥfid, basement strike, which is mainly east farther to the west, similarly swings through a northeast direction before becoming parallel with the fault zone.

Folding occurs mainly on east axes in the basement rocks over an area extending to about 65 miles north-west and north-northwest of Alḥwar. Synclinal folds with eastward plunge are mapped in the area some 16 miles southeast of Aṣ Ṣurrah, and 17 miles south-southeast of Khawrah.

In the main basement block, west of a line between Shuqrah and Mukayrās, the photogeological mapping shows large-scale folds, axes of which trend mainly northeast. A large synclinal fold plunging to the southwest is indicated about 15 miles southwest of Mukayrās. The zone of folding on northeast axes is continued to the northeast of Lawdar along a line parallel with Wādī Durā. The complicated folding here may be the result of large-scale drag effects connected with transcurrent faulting along the line of the wadi, but this has not been substantiated.

MINOR FOLD STRUCTURES

During the field reconnaissance there was little opportunity for the study of minor fold structures. Brief observations of some of these folds are recorded here.

In the main Jabal ath Thanyah range, several asymmetric plunging folds were noted. In one of these, developed in crystalline limestone, the axis trends north-northeast and the fold plunges steeply to the north-northeast. The axial plane dips steeply in a direction of 120°. The fold shows a steeply dipping eastern limb, whereas the western limb dips at a moderate angle. Other folds in this range appear to have the same orientation.

Basement rocks in Wādī Aḥwar show particularly marked minor folding and plications about axes trending 310° and plunging southeastward at low angles (fig. 22). In basement rocks to the northwest of 'Iraqh, feldspathic bands show minor folds along axes trending



FIGURE 22.—Folds in basement rocks, Wādī Aḥwar.

340°. At Jī'ār, in the Abyan district, basement rocks below unconformable Jurassic beds show small-scale folds with axes trending 310° and plunging as in Wādī Aḥwar.

The trend of the fold axes as observed at 'Irqah, Aḥwar, and Jī'ār, agrees with the strike trends plotted from aerial photographs, and thus confirms the reliability of data from the photographs. Aerial photographs show great variation in the trends of small-scale folds from one locality to another and this is attributed to differential movement between faulted basement blocks.

GENERAL

Over much of the basement-rock area, tight isoclinal folds are seen in steeply dipping belts, such as that running southeast from 'Ataq through As Sufāl, and in the belt parallel with Wādī Durā in the Khawrah district. The dip of foliation and relic bedding planes in the 'Ataq-As Sufāl belt ranges between 65° and vertical; in Wādī Durā dips of 60° to vertical were measured. In many other areas, dips between 45° and

vertical occur. In belts of steep dip, the dip direction may vary along the strike, indicating overturning. The folding appears to be of similar, as opposed to concentric, type.

In some areas, as between Aṣ Ṣurrah and Nūsah, folds of open type were seen in which dips on the fold limbs range from 15° to 30°. During the survey no obvious variation in the distribution and thickness of competent and incompetent strata was noted between areas of tight and open folding, and no explanation for variation in fold type can be given beyond the suggestion that this may be related to stress differences controlled by the alignment of ancient shear directions now marked by faults. Open folds tend to be associated with faults of mainly east trend, whereas some tightly folded belts are associated with, and run parallel to major northwest- and northeast-trending faults.

Many basement rocks give evidence of at least two major periods of stress, one associated with dynamothermal metamorphism and a later one associated with metamorphism of mainly dynamic type. Some of the evidence for two or more periods of stress is derived from the fact that the strike of foliation and relic bedding is opposed in several localities. In the Al Musaymr area, relic bedding in a quartz-biotite schist strikes at 320°; the foliation strike is about 50°. In Wādī Gharish, E.A.P., clearly visible relic bedding in garnet-staurolite-mica schist strikes at about 330°, whereas foliation strike is about 10°. In these areas the discrepancy does not appear to result from divergence of axial-plane foliation from bedding in the nose of a fold.

Further evidence for refolding occurs in the Sa'id area where fine-grained quartz-biotite gneiss shows post-crystalline deformation. The fold core shows quartz, and biotite-rich layers, and in the latter biotite flakes follow the folding, showing some minor distortion in the crestal part. This distortion is considered to be due to refolding of a foliated rock rather than to mimetic crystallization.

Petrographic evidence for renewed stress following initial development of foliation is shown in a number of specimens by such effects as crumpling of an earlier schistosity and two generations of quartz and mica. (See also "Metamorphism.")

The earlier stress period recognized seems to have affected basement rocks at considerable depth where temperature elevation enhanced by granitic invasion reduced the rocks to a partly plastic condition. Ptygmatically folded veins of granitic material, which occur in zones peripheral to syntectonic granite, are probably associated with plastic deformation of the host rock, which is also indicated by sinular folding. Many feldspathic bands and some pegmatites, folded con-

cordantly with intricately folded country rocks, provide structural evidence for syntectonic granite invasion, because the bands are associated with these granites.

Rocks showing evidence of polymetamorphism, which have undergone at least two periods of stress, are those classed as the Aden Metamorphic Group and the associated syntectonic granites. A second class of rocks shows mainly the effect of dislocation metamorphism, such as deformation of mineral components, cataclasis, and shearing. This class comprises the intertectonic igneous rocks of W.A.P. and the older volcanic and Wādī al Ghabar metasedimentary rocks of E.A.P. The later metamorphism which affected these rocks operated at effectively higher levels, owing probably to some denudation of cover rocks between the time of the earlier mesozonal metamorphism and the later epizonal effects. The latter resulted in the imposition of strain-slip cleavage upon basement rocks over a wide region, extending from southwestern Hadramut to the western part of the Protectorate. An example of this is seen in an eastern tributary to Wādī Gharish, where platy quartzitic rock is interbedded with more argillaceous sandstone. Fracture cleavage making a high angle with bedding planes is strong in the less competent member. Shear zones present in a number of areas are exemplified by that seen in the Mukayrās pass where dioritic rock of the intertectonic igneous phase is cut by shear planes at steep angles, along which is phyllonitic rock.

To summarize, the available evidence indicates at least two important stress periods. The earlier period affected basement rocks in a partly plastic state and resulted mainly in close isoclinal folding of similar type. Axial planar foliation was developed due to metamorphic recrystallization. A later period of stress appears to have caused some refolding of foliated basement rocks and folding of the later Wādī al Ghabar metasedimentary rocks. At this stage fracture cleavage was developed and is shown in the multidirectional cleavage planes of the older volcanic rocks of E.A.P. and in many of the W.A.P. basement rocks. This strain-slip cleavage does not appear to have progressed through recrystallization to the production of schistosity or gneissic banding, and it does not obliterate older structures, some of which are expressed as contortions of earlier schistosity. Shearing and cataclastic deformation also resulted from the later stress phase. Granitic intrusions of presumed early Paleozoic age have not been similarly affected.

POSTBASEMENT STRUCTURE

The structural features associated with postbasement rocks of the western part of the Protectorate must be

considered in relation to the Eastern Protectorate where by far the greater proportion of Jurassic and later rocks are exposed. Beydoun (1961) gave a full account of these rocks in E.A.P., from which data have been extracted and are included in the following discussions. Reports of restricted occurrences of Paleozoic rocks in W.A.P. (Jaques, unpublished data, 1952) have not been confirmed in the recent survey.

Late Jurassic-Early Cretaceous structure.—Beydoun reported faulting and local folding associated with faulting in E.A.P. in late Jurassic or Early Cretaceous times. He adduced evidence for movements at the end of deposition of the Shuqra Formation (Lower Oxfordian), suggesting emergence and the rise of a barrier. At the end of Shuqrah times this barrier was assumed to have isolated an evaporitic inland basin in which the Sabatayn Formation (correlated with the Medbi, overlying the Shuqra Formation) was deposited. Intrafacial conglomerates in the Naifa Formation [Upper Kimeridgian-Thithonian] indicate erosion of an emergent barrier which was overcome to allow the Naifa Formation to spread inland over the evaporitic basin, and to overlie the Sabatayn Formation as it overlies the Madbi Formation. The exact position of the postulated Jurassic barrier is not known, but it may have been aligned westward to the south of the axial region of the present south Hadramawt arch.

At the end of the Upper Jurassic, faulting took place. According to Beydoun, this appears to have been mainly block faulting, perhaps due to relaxation from uplift. The fault direction is dominantly north, but some east-trending fractures are also present.

Beydoun noted that the terminal Jurassic movements divided the territory into major north-south highs and lows, which were differentially eroded before the Cretaceous cover was laid down. The north-south features extend across the whole territory and were thought to be due to faulting along old trends in the basement rocks. The most important uplift is the Mukalla high. A subsidiary high was noted in the eastern part of W.A.P.

Over the western part of the Protectorate little information concerning Jurassic structural conditions can be obtained, as Jurassic rocks in this region are preserved as faulted blocks and strips of fairly restricted extent. Jurassic strata are preserved along the faulted escarpment extending southwestward from near 'Ataq toward the coast and also in an area of complex faulting to the south of Mayfa'ah, Al Wāhidī. From the neighborhood of Al Mabfid west-southwestward to the longitude of Aden, Jurassic together with Cretaceous rocks on the basement rocks are preserved in places by faulting in mainly east-northeast to east directions.

Jurassic rocks also occur in an area of mainly northwest faulting at and to the east of Al 'Anad.

The salt domes of 'Iyādh, Lai'adin (Ayadim) (about 38 miles N. 64° E. from An Nuqūb, Baybān) and of the Shabwah area are present in rocks of the Sabatayn Formation. The Naifa Formation is represented in the 'Iyādh dome.

Cretaceous structure.—Beydoun recorded no important faulting or folding in the Eastern Protectorate during the Cretaceous, but epirogenic subsidence and local uplift was thought to have occurred. He noted that in Aden Protectorate and in the former Somaliland Protectorate the overall trend of facies lines is north, indicating new easterly tilt of the land surface and transgressions from the east.

In the west-central subcoastal areas of the Aden Protectorate, Cretaceous beds resting upon Jurassic strata are preserved in faulted strips. To the east of a line between Ad Dālī and Al 'Anad, Cretaceous rocks crop out at the margin of volcanic rocks of the Aden Trap Series, which they appear to underlie in the south-western areas of the Protectorate. Their relation to the trap series is difficult to discern because in most places the contact is one of faulting. The balance of evidence suggests that volcanic rocks are later than exposed Cretaceous strata. At 'Awābil and Al 'Anad, Cretaceous sandstone rests directly upon basement rocks. The evidence indicates marine transgressions from a easterly direction, advancing up the slope of the tilted Arabian shield and resulting in a diminishing thickness of deposits from east to west. In the westernmost parts of the Protectorate, continental (and possibly lagoonal) deposits replace the marine deposits of the east.

Paleocene and Eocene structure.—No faulting or folding was recorded by Beydoun in the early (Paleocene) stage of the Tertiary subsidence in E.A.P., but in Paleocene and middle Eocene times the progressive development of the biaxial Hadramawt arch began. This feature attained its present form about the end of the Eocene, but the collapsed south flank resulted from faulting in the later Tertiary.

Beydoun noted that the structure is divided into north and south arches by an intervening gentle syncline, all the folds trending west-southwest in Hadramawt, but swinging to the east in Al Mahrah.

The south Hadramawt arch is intersected in the west by a zone of west-northwest faulting across its axial line, and the arch loses its identity toward the Western Protectorate border. The flanks of the folds show very gentle dips amounting to about 1° overall, but the southern flank of the south arch is in the form of a broken scarp owing to extensive faulting associ-

ated with the Gulf of Aden rifting. Beydoun regarded the arching as due to warping rather than faulting.

Eocene sedimentary deposits are barely represented in W.A.P., but the Eocene structural history of E.A.P. is relevant to the study of the W.A.P. structure. The Hadramawt folds discussed by Beydoun (1961) are shown on plate 2. The fact that these die out in the region of a major fault zone of northwest trend, which throws strata to the east against western basement rocks, reinforces stratigraphic evidence for thinning of Eocene deposits to the west and suggests that the fault zone referred to was active in Eocene times, being associated with basement uplift and reduced sedimentation. In view of the occurrence of Eocene sedimentary rocks at Al Mahfid, west of the present-day faulted escarpment, it cannot be postulated that the fault zone referred to limited the westward extension of Eocene deposition. Nevertheless, it would seem that this zone of faulting lies on or near the eastern border of a regional uplift that resulted in the present exposure of the main mass of basement rocks in W.A.P. To the west of this fault zone all strata of Jurassic and later age are in faulted relationship to basement rocks, as opposed to forming an extensive cover, as is true to the east. The near-complete absence of down-faulted remnants of Eocene rocks over the western area strongly suggests that these were not deposited over most of the region.

It may be inferred that the elevation of the basement rocks in the western part of the Protectorate formed a barrier to the westward advance of Eocene transgressions. This elevation was of epirogenic type. It is reasonable to correlate this uplift with the incidence of volcanic activity of Late Cretaceous or early Tertiary age that occurred in the southwest. The original eastward limit to the spread of these volcanic rocks of the Aden Trap Series is not known but they are separated from uplifted basement rocks by faulting, a major zone of which trends north-northwest to the east of a line between Ad Dālī and Al 'Anad. The extension of the eastern boundary of the volcanic rocks into Yemen, as mapped by Geukens (1960), suggests that the volcanic rocks are preserved in a depressed zone flanked to the east by a tectonic ridge trending generally north-northwest.

Oligocene and Miocene structure.—Beydoun stated that subsidence and progressive marine incursion from east to west occurred in the Gulf of Aden during the Oligocene and Miocene times, and he considered that during this phase of relaxation from compressional uplift, associated with the development of the Hadramawt arch, normal faulting parallel to the axis of folding broke up the south flank of the (south) arch. Coastal Oligocene and Miocene deposits (Shihir Group)

have been tilted by fault movements, which Beydoun considered to predate Gulf of Aden faulting.

Neogene and Recent structure.—Beydoun considered Gulf of Aden faulting of east-northeast trend to be fairly common; he noted long straight stretches of coastline which follow this direction and which have undergone relative elevation in Neogene to Recent times, as shown by the fact that Oligocene and Miocene deposits are involved in the uplift. Evidence for faulting of Oligocene and Miocene deposits is lacking in W.A.P. where such deposits are not recorded. Relative uplift of the land is shown by terraces of alluvial material standing at heights of 35–75 feet above incised wadi course. In Wādī Abwar a well-developed oxbow isolated some 35 feet above the present wadi bed indicates a period of stability followed by a very recent change of base level. Faulting in basalt flows of the Aden Volcanic Series between Shuqrah and Abwar, aligned in the Gulf of Aden trend, indicates late epeirogenic movement, probably in Recent times.

Summary.—The very extensive folded sedimentary cover of Jurassic to middle Eocene rocks of E.A.P. does not occur west of a northwest-trending fault zone which extends from near 'Ataq to the coast a little east of 'Irqah. This fault zone may continue to the northwest, under the sands of the Ramlat as Sab'atayn, to link with major faults of the same trend that are mapped in Yemen.

To the west of this fault zone, in the subcoastal region of west-central Aden Protectorate, Jurassic and Cretaceous strata are preserved in restricted elongate outcrops faulted against the basement rocks by faults of east-northeast to east trend. The Cretaceous rests upon Jurassic and the latter upon peneplained and weathered basement rocks. Recorded Eocene in W.A.P. is limited to an exposure in a small down-faulted syncline at Al Mahfid.

In the southwest of the Protectorate, east of a line between Ad Dāli' and Al 'Anad, a second major fault zone trending generally north-northwest, with northwest components, marks the western edge of the main basement block of the Protectorate. Jurassic and Cretaceous beds are exposed in faulted strips along this zone. At 'Awābil, Al 'Anad, and elsewhere in this western region, Cretaceous sandstone rests directly upon basement rocks. West of the fault zone an extensive area of volcanic rocks of the Aden Trap Series occurs. As suggested by Geukens in the case of Yemen (1960, p. 178), it is considered that these volcanic rocks are underlain by Cretaceous sandstone of Nubian type. The volcanic rocks are of Late Cretaceous or more probably Tertiary age. They are cut by faults which very generally trend northwest,

and this trend is also followed by many dikes of the area.

It is considered that the Aden Trap Series and the underlying Cretaceous sandstone, which is preserved from denudation by the volcanic cover, occupy a structurally depressed region flanking a tectonic high to the east. The high was caused by epeirogenic uplift associated with faulting. A causal relation between uplift and volcanic activity is recognized and it is likely that uplift occurred in latest Cretaceous or early Tertiary times and formed a barrier to the westward extension of the Eocene transgression of E.A.P. The Aden Trap Series is regarded as roughly coeval with Paleocene of E.A.P. The fault zone east of the Ad Dāli'-Al 'Anad line lies along the western flank of the uplift, and along an extension of this north-northwest-south-southeast line into Yemen there is evidence of erosion of Jurassic and Cretaceous deposits and diminution of thickness of volcanic rocks (Geukens, 1960, p. 139, 153–154). Geuken's map of Yemen completed the picture in Aden Protectorate of volcanic and sediments thinning out against uplifted basement rocks, although the fault zone which marks this uplift in the Protectorate is not (yet) mapped in Yemen.

The eastward extension of the uplift barrier cannot be exactly defined, but it is noted that the northwest-trending fault zone passing near 'Ataq, and probably linking with similar faults in Yemen, demarcates the eastern extent of the main basement block in both Aden Protectorate and Yemen, and may lie along the eastern flank of this basement uplift.

The assumption of an uplift in Late Cretaceous to early Tertiary times, associated with faulting along trends roughly parallel to that of the Red Sea axis (with which direction many eruption fissures of the trap series in Yemen are coincident (Wissmann and others, 1942, p. 290), suggests recognizable manifestations of development of the Red Sea rift dating from this time.

FAULTING

Main fault directions in the Gulf of Aden region are classified as follows. The east African trend ranges from north to north-northeast; the true Erythrean or Red Sea trend is northwest, but faults following a west-northwest direction may be included in this class; the Gulf of Aden trend is east-northeast and in strict usage should be differentiated from the east Somali trend; however, this distinction is not everywhere adhered to; the Aulatic trend is northeast.

The major faults of W.A.P. and southwestern Hadramawt are shown on plate 1. The fault pattern

over a wider region of southern Arabia and the former Somaliland Protectorate is shown on plate 2.

FAULTING OF EAST AFRICAN TREND

Faults of east African trend are of somewhat restricted and generally local occurrence. They are mapped in the basement rocks of the Baybān area, in the Jibāl an Nisīyān block, and to the northeast of Abwar; also in other basement-rock areas. An extensive fault following the line of Wādī Raybān, to the southwest of Lawdar, maintains a north-northeast trend along much of its length before swinging to a northeast direction in the north. Although faults of this class may follow basement strike direction, this is not always true; southwest of Lawdar and southeast of Khawrah, faults cut across foliation strike at high angles.

In many places faults of east African trend are displaced by those of Gulf of Aden trend (s.l.). Thus in E.A.P., faults bounding the Wādī al Ghabar metasedimentary rocks are aligned approximately along the east African trend and terminate against and are offset by east-trending faults. Faults of west-northeast trend also appear to be of later date in this locality.

FAULTING OF RED SEA TREND

Faults following the Red Sea trend, as loosely defined, form an important feature of the Protectorate fault pattern.

The 'Ataq fault zone.—A major zone of faulting of Red Sea trend extends for over 60 miles from near 'Ataq to the locality of 'Irqah in the coastal plain. The northwest-trending faults, dominant in this zone, both offset and are offset by east-trending and west-northeast-trending faults, and may swing to the west-northwest direction. It is probable that this zone of Red Sea faulting extends into Yemen through the Ramlat as Sab'atayn.

The 'Ataq fault zone marks the eastern border of the main block of basement rocks of the Protectorate and over much of its length is parallel with the strike of basement rocks immediately to the west. Farther to the west the basement strike trends roughly east but swings into parallelism with the fault zone. A prominent faultline scarp is formed by sedimentary rocks to the east, which dip away from the basement junction in a general northeasterly direction. The present surface expression is of normal faulting, which has thrown down Jurassic and later sedimentary rocks against basement rocks (fig. 23). Where observed near As Sufāl, the dip of the fault plane is steep and there is evidence of variation of apparent vertical displacement along the

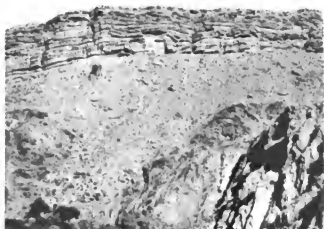


FIGURE 23.—Jurassic limestone faulted against schist along part of the 'Ataq fault zone, As Sufāl.

fault strike. It is possible that transcurrent faulting at depth, of ancient inception, is expressed by later vertical movement at the surface, and this theory may also be supported by the rectilinear trace of the main faults.

The Dhala fault zone.—Bounding the main basement block to the west is a second major zone of faults of Red Sea trend (s.l.) in which the characteristics of a fault zone are more clearly expressed by numerous faults trending north-northwest and northwest. Faults of the general Gulf of Aden trend that occur here appear to be mainly of later date.

The Dhala fault zone, some 6-7 miles east of a line between Aq Dālī and Al 'Anad, separates basement from volcanic rocks of the Aden Trap Series and along the margin of the basement rocks, faulted blocks of Jurassic and Cretaceous sedimentary rocks are preserved; these dip away from the basement rocks in a general southwesterly direction. The faulting also preserved the volcanic rocks—of Late Cretaceous or Paleocene age—in the downthrown basinal region to the west; the inception of the faulting in Late Cretaceous or Paleocene times is indicated by the absence of volcanic rocks to the east of the fault zone. If the fault zone postdated volcanic activity, preserved volcanic remnants might be expected to occur over the basement rocks to the east, as is true of Jurassic and Cretaceous rocks. Alternative explanations for the absence of volcanic rocks east of the fault zone involve nondeposition of these east of a fairly sharp line of demarcation, or cessation of down faulting over the basement-rock area subsequent to the Cretaceous Period. Both these postulates are highly improbable.

Faulting in the Aden Trap Series.—The Red Sea trend (s.l.) is dominant in faults cutting the Aden Trap Series in the southwest of the Protectorate and many of these faults follow the true northwest-southeast Red Sea direction. The volcanic rocks were originally disposed in subhorizontal sheets, but over much of the area they are tilted by strike faults and dip generally to either the northeast or southwest. In several areas, for example, southwest of Al Musaymir and northwest of Ghayl Barbar, Cretaceous sandstone is exposed in the volcanic area by faults of Red Sea trend.

The 'Iyādh fault zone.—In southwestern Hadramawt a zone of faults trending west-northwest to northwest, expressed largely in Eocene sedimentary rocks, can be followed from 'Iyādh to the locality of Neifa on Wādī Ḥajr. Here the clear expression of this trend is lost in complex faults that follow several directions. Against this zone of faults of Red Sea trend (s.l.), the southern anticlinal fold of the Hadramawt arch fades out. To the east, faulting in the sedimentary cover trends dominantly east or east-northeast. Although faulting on west-northwest lines occurs in the Ra's Sbarwayn-Ra's Fartak area, it is likely that this differs from the 'Iyādh zone of faulting in origin and time of initiation. Beydoun (1961) suggested that some of the faulting on west-northwest lines may have developed during the culmination of geanticlinal warping as a form of adjustment to differential crustal shortening, and he suspected that some transcurent movements involving the Gulf of Aden trend may be associated.

The zone of faults extending southeast from 'Iyādh is flanked at its southeastern end by an area of exposed basement rock that extends eastward to Al Mukallā. Beydoun (1961) recorded an old high of igneous basement rocks in the Al Mukallā area. He suggested that this feature was formed by uplift during post-Jurassic faulting but that this movement could have been one of rejuvenation. These observations support the suggestion that the 'Iyādh fault zone is the expression of a reactivated ancient fault trend connected with the uplift of the Al Mukallā high and resulting in a complementary depressed area between this and the main block of presently exposed W.A.P. basement rocks to the west, the latter being also margined by the 'Ataq zone faults of Red Sea trend. In this depressed zone, basement exposures are limited, although the elongate basement range of Jibāl al Aswad forms a prominent feature flanked by west-northwest-trending faults parallel with the foliation strike. The expression of rejuvenated(?) Red Sea trend faulting (s.l.) in the sedimentary cover of the depressed zone, as contrasted with the greatly reduced expression to the east, may be related to the reduced thickness of Tertiary cover,

which is also reflected in the fading of the Hadramawt arch to the west. It is noted that in former Somaliland Protectorate, faults of Red Sea trend (as other faults), that extend inland from the sunken coastland (basement) region die out as they penetrate the sedimentary plateau (Somaliland Oil Exploration Company, Ltd., 1954, p. 33-34).

Apart from the zones mentioned above, faults of Red Sea trend (s.l.) occur over much of the basement-rock region; they may cut across foliation strike directions as in the Wādī Banā area southwest of Mukayrās, and in the Baybān area. These faults may throw to northeast or southwest. In Wādī Abwar a small reverse fault, striking northwest, dips steeply to the northeast and throws down to the southwest.

FAULTING OF AUALITIC TREND

Faults following the northeast Aualitic trend, parallel with the main Ethiopian rift direction, occur in the western part of the Protectorate, as in Yemen, but they are comparatively few. In the E.A.P. significant faulting on this trend is apparently not recorded. In common with faults of other classes, faults of Aualitic trend may swing to follow other trends.

A major fault of this trend runs for some 25 miles parallel with the fault scarp of the Kawr al 'Awādhil passing to the north of Lawdar. It is probable that this fault, or a parallel fault, extends farther to the northeast along the Wādī Durā. The fault follows basement strike.

In the region to the east of the upper Wādī Banā, faults of Aualitic trend are somewhat transverse to basement-rock strike. The longest of these can be traced for 25 miles before it swings to an east-northeast direction in the southwest. Other faults of the same trend cut basement rocks and Jurassic and Cretaceous rocks northwest of Ar Rawdah, to the north of Aden, and in the area south and southeast of Baybān.

FAULTING OF GULF OF ADEN TREND

As noted, the Gulf of Aden trend strictly refers to faults trending east-northeast. Many faults that follow this direction over part of their course swing to east or even west-northwest trends. These are all included under Gulf of Aden trend (s.l.).

The distribution of Gulf of Aden faults in W.A.P. is fairly uniform except that their expression is much restricted in the Aden Trap Series in the southwest. Few of the individual faults of this class are of great length, but a nearly continuous line of faults some 28 miles long through Wādī Ḥabbān and Yashbum is noted. Further extensive faults on the same trend occur south and southwest of Al Maḥfid.

Faulting of the Gulf of Aden trend is mainly responsible for the preservation of elongate strips of Jurassic and Cretaceous sedimentary rocks in the basement-rock area in the coastal zone between the longitudes of Aden and 'Irqah. The width of these faulted blocks generally does not exceed 4 miles and in many places is less than 1 mile; in length a practically continuous strip extends for some 80 miles. Traverses inland in a north-south direction may cross four or more of these faulted blocks with intervening basement rock or basalts of the Aden Volcanic Series, as between Shuqrah and Lawdar. The characteristics of many of these faulted blocks is exemplified by that occurring some 30 miles northwest of Abwar. Here Jurassic limestone is preserved by normal faults striking parallel with, and dipping northward in the same direction as, basement strata—that is, parallel with basement bedding planes. The Jurassic beds of the tilted block dip southward in the opposite sense to basement foliation (and relic bedding) and rest upon basement rocks to the north. Similar fault blocks occur to the northwest of Shuqrah and at the northern edge of the coastal plain north of Aden; in these blocks tilted sedimentary beds dip at about 25° – 30° S. against strike faults downthrown to the north. The dip of the fault planes is about 50° . In some places the faults throw sediments down against basement dip in the opposite sense to basement foliation, as in the area 8 miles west of Nūṣah, where faults are downthrown to the south.

Wissmann, Rathjens, and Kossmat (1942, p. 293) recorded, near the foot of the Kawr al 'Awādhil, narrow ridges of basement rocks bearing nappes of Jurassic limestone dipping south-southeast. These form narrow fault blocks bounded by faults that strike east-northeast and dip north-northwest. The distance from fault to fault is estimated at 2–3 km on the horizontal, so that a "staircase" of narrow fault blocks is formed. The fault planes dip in the opposite direction to the faulting responsible for the main scarp. With respect to this main fault, the faulting of the stepped blocks may be described as antithetic. The fault planes of these blocks run parallel with the (relic) bedding planes of the basement rocks which form preferred directions for the downthrow faults. Wissmann suggested that the tilt direction of the faulted sedimentary blocks is inversely related to the dip of the basement strata.

These observations accord with the relations seen in many of the faulted sedimentary blocks in basement-rock areas; but as noted above there appears to be no constant relation between the direction of throw of the faults, and hence tilt of the blocks, and dip direction of the basement rocks.

Although faults of Gulf of Aden trend in several areas, and particularly in the west-central part of the Protectorate, run parallel with basement strike, this coincidence is not universal.

A few faults of Gulf of Aden trend occur in basalts of the Aden Volcanic Series, between Shuqrah and Abwar.

In E.A.P., faults trending east and east-northeast are numerous, particularly on the south flank of the Hadhramut arch, as noted by Beydoun (1961).

GENERAL

Faults in the Aden Protectorate are generally of normal type, as expressed at the surface. Minor reverse faults occur in basement rocks, as in the Abwar district, and a small thrust fault involving Cretaceous and Jurassic beds is recorded in the lower Wādī Ḥajr of E.A.P.

In some places the normal fault probably represents the latest increment of movement along ancient shear directions in which earlier deeper movements were of transcurrent or wrench faulting. This seems particularly likely for northwest- and northeast-trending faults, which show long and straight traces and in which the dip of the fault plane is high. Faulting on these trends may occur as a complex zone, which is again a common expression of deep wrench faulting. Considerable variation in throw along the strike of these faults is seen.

Although shear planes in basement rocks are widely seen, no conclusive evidence for transcurrent faulting can be presented. However, aerial photographs of folded basement rocks in an area south of Al Maḥḥid show long and straight faults on Gulf of Aden trends, in which displacement of steeply dipping beds may be as much as 800 yards (fig. 24). In E.A.P., faulting in a west-northwest direction was suspected by Beydoun (1961) of being related to transcurrent movement, and he suggested tangential stress, due to horizontal components of fault movement, as a factor in the development of salt diapirism.

In former Somaliland Protectorate, in a similar tectonic setting, faults of Red Sea trend (a) show high-angle to vertical dip of fault planes; (b) frequently attain a large throw and then die out abruptly; (c) may occur as scissor faults; (d) are frequently arranged en echelon; and (e) have generally straight courses. These characteristics may be the surface expression of buried wrench faults. It must be added, however, that mylonitized zones were not recorded by Somaliland Oil Exploration Company, Ltd. (1954).

For the present it must be enough to recognize that a number of the major faults of Aden Protectorate may



FIGURE 24.—Faults and folds in basement rocks, about 8 miles south-southeast of Al Mahfid. The trace of a major fault extends across the southern part of the area in a direction nearly east-west. To the north, Jurassic beds (1) are faulted against the basement. Royal Air Force photograph. Crown copyright reserved.

be of ancient origin and originally of transcurrent type. Rejuvenation of ancient trends is suggested and although periods of marked vigor are recognized from Late Jurassic onward, these probably represent phases in a much longer succession of movements.

AGE OF THE FAULTING

Observations on faulting over a wide region show that the faulting of any one trend was not confined to a single period. It is, however, possible to be more specific with regard to the dating of certain main periods of faulting.

Evidence has been given to suggest that important phases of faulting on Red Sea trends date from Late Cretaceous or Paleocene times. Along Ad Dālī'-Al 'Anad fault zone Cretaceous beds rest directly upon basement rocks in some localities. This may indicate faulting and erosion prior to Cretaceous deposition, because Jurassic strata are preserved upon basement rocks elsewhere in the same general area. Northwest-trending faults affect middle Eocene strata in the Mayfa'ah district and elsewhere in E.A.P., but faulting on this trend does not appear to cut Oligocene and Miocene coastal deposits, at least to as far east as long 50° E., which marks the limit of photogeological mapping. Much faulting on west-northwest lines is present in the Eocene of E.A.P., and Beydoun (1961) suggested that this may have occurred at the culmination of geotectinal warping, presumably in Late Eocene times.

On the evidence available, it is suggested that faults of Red Sea trend (s.l.) date from at least Late Cretaceous times, with a possible earlier inception in the Late Jurassic. There are no data proving faulting in this trend later than late Eocene.

In W.A.P., Gulf of Aden faulting in at least two periods is shown by the fact that Red Sea faults both offset and are offset by faults of Gulf of Aden trend. A number of the latter faults, expressed in basement rocks, terminate against northwest-trending faults of the 'Ataq fault zone, and do not appear in Jurassic and later sedimentary rocks to the east. In former Somaliland Protectorate, erosion and removal of Jurassic strata over large areas may indicate extensive Jurassic, or Early Cretaceous, faulting, and Somaliland Oil Exploration Company, Ltd. (1954, p. 37) suggested the possible existence of an early Somaliland plateau, trending roughly east-northeast, in Early Cretaceous times. This may result from Gulf of Aden faulting dating from this period.

No direct evidence as to the date of initiation of a more recent period of Gulf of Aden faulting is obtainable from W.A.P., but in E.A.P. Oligocene and Miocene deposits are banked against older strata in

the coastal areas east of Al Mukallā; these deposits resulted from subsidence and marine transgression over a coastline parallel with the Gulf of Aden axis. As in Somaliland, their distribution indicates the existence of a Gulf of Aden at this time. The deposits are tilted by faults of Gulf of Aden trend.

It seems clear that a main phase of Gulf of Aden faulting dates from Oligocene or early Miocene times. Continuation of this faulting into Pliocene, or probably Recent, times is shown by the following observations:

1. Long sections of coastline following the Gulf of Aden direction were elevated in Neogene to Recent times, as indicated by reef deposits of Miocene age involved in the uplift.
2. The final breakdown of the Red Sea-Indian Ocean barrier has been referred, on fossil evidence, to middle Pliocene times (Cox, 1931). This indicates Gulf of Aden movements at this date.
3. East-trending faults have been mapped in basalts of the Aden Volcanic Series between Shuqrah and Aḥwar. The basalts are considered to date from late Miocene or Pliocene to Recent times. Many of the flows in the Shuqrah area are of very recent origin.

With regard to faults of east African trend, in the basement rocks of W.A.P. these both offset and are offset by faults of Gulf of Aden trend. That a number of east African faults terminate against faults of Gulf of Aden trend suggests that some faults of east African trend are either contemporaneous or of later date. As similar relations exist vis-a-vis faults of Red Sea trend, east African faulting may be both older and younger than faulting of other trends. It is, however, noticeable that no major faults of east African trend are expressed in the sedimentary cover of E.A.P. Movements at the end of the Jurassic in E.A.P. resulting in major highs and lows, may have been due to faulting on north-south lines, possibly along basement strike directions. Rejuvenation of ancient faults may be suspected.

Faulting of the northeast-southwest Aulatic trend is seen in the W.A.P. basement rocks and to a lesser extent in Upper Cretaceous and Paleocene volcanic rocks in the southwest of the Protectorate, but it is not recorded in the sedimentary cover of E.A.P. In the region of the upper Wādī Banā numerous faults of Red Sea trend terminate against a major northeast-trending fault, which may suggest the prior origin of the northeast-trending fault. To the southeast of Niṣāb, faulting of Aulatic trend is offset by Gulf of Aden faulting. Thus faulting of northeast trend is earlier than at least some of the faulting of other trends, but definite evidence as to the age of this faulting is lacking.

GENERAL COMMENTARY ON STRUCTURE

Many workers have made reference to the structural history of the Gulf of Aden and surrounding region, which is of particular interest insofar as it includes the confluence of the tectonic features of the Red Sea, Gulf of Aden, and Ethiopian rifts. Mention may be made of the work of Gregory (1921), Krenkel (1925), Lamare (1936), Picard (1937), Cloos (1939), Wissmann, Rathjens, and Kossmat (1942), and Carey (1958), although this by no means exhausts the list. There is considerable divergence in the views expressed, centering mainly on the relative importance of tensional, compressional, and drifting mechanisms.

Hitherto few data have been available regarding basement strike and faulting pattern in W.A.P. Of the several main hypotheses that might be advanced to explain the broad structural features of the region, that based on the concept of the regmatic shear pattern shows most promise of eventual reconciliation with the facts. This concept has developed through the work of Hobbs (1911), Vening Meinesz (1947), Moody and Hill (1956), and others. The term "regmatic shear pattern" was introduced by Sonder (1947).

According to this concept the earth's crust is intersected by major shear lines of worldwide distribution, those directed northwest and northeast being primary shear directions. The primary shear directions may be associated with subsidiary directions trending north and east, and in other directions orientated symmetrically with regard to the major primary stress. The actual expression of shearing may depart from the directions derived from purely theoretical considerations. These shear lines are considered to be of ancient—primordial—origin but are subject to reactivation at various periods following renewal of stress, which may result in further transcurent shearing, or in tension or compression. Stress acting upon a segmented crust may result in differential movement along margins of basement blocks, in block jostling, and in complex movement of basement blocks beneath a sedimentary cover. As noted before, transcurent or wrench faulting at depth may be translated into essentially vertical movement at the surface.

It is beyond the scope of this paper to consider in detail the evidence for the existence of these ancient shear zones, but it is noted that Precambrian effects associated with, and aligned along, Jurassic and Tertiary east African rifts include thrusting, shear zones, mylonitization, igneous intrusion, and migmatization. Stocks' (1941) chart of the Gulf of Aden shows a series of submarine ridges and channels in the eastern part of the Gulf which trend northeast along a primary shear direction.

Considered in terms of the regmatic shear pattern, the fault pattern of the Protectorate may be resolved into primary northwest and northeast shear directions and subsidiary shear directions, among which the Gulf of Aden east-northeast trend would be classed as a second-order shear direction.

The major fold axes of the Protectorate basement rocks trend in various directions, but this of itself does not necessarily imply differing directions of primary stress. Evidence on the earlier structural history of the Protectorate clearly suggests a number of major features trending generally north. In the E.A.P. occurs the basement-rock high of Al Mukallā; the main basement block of W.A.P. may represent a swell trending generally north; terminal Jurassic movements in E.A.P. are thought to have divided the territory into major north-trending highs and lows. Old north structural trends are known in several areas in south Arabia and a system of meridional troughs and swells may be suspected in this region. These observations might suggest that stress affecting the older rocks of the Protectorate involved a dominantly east, rather than north, component, and this is supported by the fact that in the north part of the Protectorate, away from the influence of the Gulf of Aden shear zone, the basement strike shows a strong north component which is continued over much of western Saudi Arabia and Yemen. (In Saudi Arabia folds trend mainly north, northeast, and northwest. In Yemen the older Wadi Medina Series strikes generally north.)

It is probable, however, that most, if not all, of the highs referred to were due to, or accentuated by, faulting following regmatic shear directions. The question arises as to the nature and orientation of the stress causing these faults. There is no direct answer to this, but the mechanism of uplift may have been controlled by faulting along northwest-southeast lines resulting from primary compressional stress in an east-west sense. The main basement block is bounded to the east and west by faulting on these lines; that the elevation of Al Mukallā high is also due to such faulting is to some extent supported by the fact that the complementary depressed area to the west of Al Mukallā is also bounded to the east by a fault zone of Red Sea trend. That faulting of this trend was originally of transcurent type and was caused by dominantly east-west stress is supported by evidence from western Saudi Arabia. Here, Brown and Jackson (1960) recorded a number of major northwest-trending faults, of which the most prominent, the Nejd wrench fault, apparently shows sinistral movement, as the northern block, has moved westward with respect to the southern block. The entire pattern was said to be

that of a regional force couple. It was also noted that slight movement is seen in the Cambrian and Ordovician sandstone where the Nejd fault disappears beneath the Paleozoic basin to the north but no evidence of movement was seen beneath Permian limestone at the southeastern extension. Indications that major northwest-trending faults in the Protectorate may have originated as transcurrent movements have been noted elsewhere. In summary, it seems likely that the general direction of stress causing these faults was east-west.

It has been stated that the basement strike direction swings from being aligned roughly parallel with the Gulf of Aden to becoming parallel with the northwest-trending 'Ataq-Iraqh fault zone. This could result from transcurrent movement along this zone and the consequent drag effect on deeply buried basement rocks, but the observed structure of the wider basement-rock region could not result from movement along faults of Red Sea trend only. The structure observed is, however, commensurate with movements reflected from major northwest-trending fault zones (possibly represented by the 'Ataq zone and its extension into Yemen, and a zone aligned along the Red Sea axis) in combination with similar movements along a zone parallel with the Gulf of Aden. The overall trend of basement strike in the southern more coastal region of W.A.P. is approximately parallel with the geosuture now marked by the Gulf of Aden and provides an example of folding and foliation parallel with the controlling fracture belt. In the northern part of W.A.P., the influence of the Gulf of Aden geosuture wanes as a controlling factor in basement structure, and a more complicated pattern results from the increased influence of shear zones of other trends.

The preceding suggestions are necessarily speculative, but it is considered that some such translation of an east-west primary stress, transmitted through transcurrent movement along ancient shear zones, best fits the observed structure. Relatively minor and local variations in stress distribution is attributed to basement block jostling.

The structure of the older basement rocks may, with some confidence, be attributed to the interplay of shearing movements along different trends and may be ultimately related to a primary east-west stress. It is somewhat difficult to explain in the same context the more uniform approximately north strike of the Wādī Ghabar metasedimentary rocks and their suggested equivalents in former Somaliland Protectorate, the Inda Ad Series. There is evidence from the Arabian shield region, as elsewhere, that shearing and transcurrent movements at depth are commonly not reflected along the same fault zones at higher levels,

where vertical movement is apparent. It is therefore possible that with reference to the latest (uppermost) Precambrian rocks of Wādī Ghabar and the Inda Ad Series, no effective reorientation of the primary east-west stress has occurred.

Postulation of east-west stress as the controlling factor in basement tectonic rocks must be reconciled with the later fold structures of E.A.P., where the folds of the Hadramawt arch, expressed in Eocene sedimentary strata, trend east-northeast to east. Beydoun (1961) regarded this feature as due to warping and possibly resulting from regional compression connected with some transcurrent movement along the Gulf of Aden. The dips on the flanks of this arch are very low—generally about 1°. It seems equally possible that the arching is due to faulting and flexuring connected with the Gulf of Aden graben, essentially as outlined by Wissmann, Rathjens, and Kossmat (1942). Certainly much of the normal faulting on Gulf of Aden lines in W.A.P., which has led to the preservation of tilted blocks of Jurassic and Cretaceous strata in basement-rock areas, is attributed to tension accompanying the later phases of the formation of the Gulf of Aden.

It seems clear that although the Gulf of Aden rift is here considered to be aligned along a compressional shear zone of ancient origin, the latest manifestations of rift formation are of tensional type. Since Oligocene and Miocene times, and probably since Late Jurassic times, movements in the Gulf of Aden have been epeirogenic. In this movement, the fault zone of the Gulf of Aden appears to have become depressed relative to the intermittently rising plateau areas on either side of the Gulf.

SUMMARY OF GEOLOGICAL HISTORY

The following sequence of events is suggested for the western part of the Aden Protectorate:

1. Deposition of sediments, probably upon a planed surface of older gneiss, accompanied by volcanic activity.
2. Intrusion of mafic igneous rocks.
3. Folding and regional metamorphism of sedimentary and mafic igneous rocks to form the Aden Metamorphic Group, accompanied by syntectonic granite invasion, granitization, and migmatization. The metamorphism was mainly of mesozonal type, reaching grades appropriate to the almandine-amphibolite facies.
4. Intermittent uplift of the region.
5. Intrusion of intermediate to mafic plutonic rocks, mainly dioritic, followed after a short interval by intrusion of calc-alkaline granite. Production of contaminated rocks. (In E.A.P. approximately

contemporaneous extrusion of andesitic volcanic rocks occurred.)

6. Major phase of silicic and mafic dike intrusion.
7. Uplift and denudation of the region and deposition of sediments so derived in fairly local basinal areas. These deposits are represented by the Ghabar Group of E.A.P., but apparently are not preserved in W.A.P.
8. Widespread epizonal metamorphism mainly characterized by deformation, shearing, cleavage, and cataclasis.
9. Planation of basement rocks, followed by deposition of lower Paleozoic sediments. (This stage is particularly conjectural and based on data from adjoining regions.)
10. Intrusion of posttectonic calc-alkaline granites, some of which are dated by radioactivity methods as of Cambrian age. Certain mafic plutonic intrusions may have been emplaced at this stage.
11. Phase of mainly mafic dike intrusion.
12. Widespread pre-Jurassic denudation and planation. The time or times of this planation cannot be closely defined.
13. Deposition of Jurassic and Cretaceous sediments, which are separated by an unconformity or disconformity. Cretaceous rocks may rest directly upon basement rocks.
14. Volcanic activity in the southwest of the region, resulting in formation of the Aden Trap Series of Late Cretaceous to Tertiary age. Intrusion of alkalic granite and of silicic and mafic dikes.
15. Deposition of Paleocene to lower Eocene sediments in the east of the region. A disconformity separates these from underlying Cretaceous rocks.
16. Volcanic activity resulting in the Aden Volcanic Series, of late Miocene or Pliocene to Recent age.
17. Formation of superficial deposits, terraces, raised beaches, and dune sands, from Pliocene and Pleistocene times onward.

Certainly since Mesozoic time and probably since the end of the Precambrian, the region has undergone intermittent epirogenic movements, which continued until Recent time and were associated with faulting. Faulting is probably of ancient origin with repeated rejuvenation along old trends. A phase of faulting in the Red Sea trend dating from at least Late Cretaceous until late Eocene time is recognized. A main phase of faulting in the Gulf of Aden trend dates from early Miocene time.

ECONOMIC GEOLOGY GEOCHEMICAL PROSPECTING

Geochemical prospecting (as defined by Hawkes, 1957) is a method of mineral exploration based on

systematic measurement of one or more chemical properties of a naturally occurring material, the purpose of which is to define areas where the chemical pattern, known as a geochemical anomaly, indicates the presence of ore minerals. The chemical property normally measured is the trace content of various metallic elements and the naturally occurring material may be rock, soil, wadi sediment or water.

Two kinds of geochemical anomalies are (a) primary, of deep seated origin, resulting either from local variations in original rock composition or from impregnation of rocks by mineralizing fluids, and (b) secondary, of superficial origin, resulting from weathering of rocks and ores in situ and of material dispersed from its original source by gravity or running water. Anomalies of the secondary type were sought during the 1961-62 survey, which involved sampling the finer fractions of transported wadi sediments.

In the Protectorate, mechanical disintegration is predominant, causing oxidized ore to be released slowly as the rock weathers. Slope wash carries the metals, along with other soil materials, into nearby wadis where they are incorporated in the alluvium and moved downstream by occasional floods. Owing to the soft nature of most oxidized ore minerals, they are susceptible to abrasion; sampling of the finer fractions of wadi sediments thus offers the best prospects of detecting metal concentrations, but a rapid fall off in values away from an ore body may be anticipated in view of the lack of running water. In an investigation of an outcropping copper ore in an arid part of the United States (Lovering and others, 1950), anomalous values could be detected in alluvium more than 1 mile below the ore body, although the copper decreased from 6,500 ppm (parts per million) over the ore body to 650 ppm only 500 feet downstream.

SAMPLING

During the course of the 1961-62 survey, 308 samples of -80 fraction material were collected from drainage channels at fairly regular intervals along the route, depending on the availability of suitable sampling sites. Where the road crossed small wadis, these were sampled; where it lay along the major wadis, as was frequent, tributary wadis on either side were sampled. The sampled wadis had in common a small catchment area of a few square miles—which could be defined on the aerial photographs—where the effects of possible outcrops of mineral veins or ore bodies would not become diluted by the addition of large volumes of alluvial material.

RESULTS

Values generally were low, indicating a weak dispersion of the elements; no samples showed very high

values, but areas could be delimited showing a relatively higher content of certain metals. Of particular interest were the following areas which showed relatively high values for a combination of elements:

Copper, zinc.....	Al 'Anad area.
Copper, nickel, chromium.....	Minādī-Sanāb area (north of Ad Dālī).
Copper, zinc.....	South of Al Kirsh.
Copper, lead, zinc.....	'Alī 'Abd Allāh area.
Nickel, chromium.....	Minādī-Sanāb area: east of Mukayrā, and southeast of As Surr (near Nisāb).
Copper, zinc.....	Southeast of 'Ataq.
Nickel.....	Eastern branch of Wādī Ḥusaybah (E.A.P.); west of Jabābān.
Copper, zinc.....	Wādī Ḥimam (E.A.P.).
Zinc, nickel.....	Wādī, 10 miles west of 'Irqah.
Nickel, chromium.....	Wādī Dayqah (Abwar).

INTERPRETATION OF RESULTS

One of the principal problems in interpreting the data is to distinguish geochemical anomalies from dispersion patterns of no economic significance. Certain empirical parameters can be applied which are helpful in identifying and interpreting the anomalies. These involve considerations of (a) the range of nonsignificant variations in the background, (b) the threshold between nonsignificant and anomalous values, and (c) the homogeneity of the anomalous pattern. Unfortunately, little work has been done on dispersion patterns under an arid weathering regime such as prevails in the Aden Protectorate, and guidance cannot be obtained from experience elsewhere. Normally, geochemical data obtained in areas where the equilibrium has not been upset by the presence of a mineral deposit lie within statistically well-defined limits; patterns of variations may occur, but still lie within this background range. In interpreting the geochemical pattern of an area containing anomalies, it is usually possible to select a certain limiting cutoff or threshold value below which the variations represent background effects and above which they may have significance in terms of possible ore. No hard and fast rules concerning the threshold value can be established, as the geochemical factors may be different in each particular area. In the Aden Protectorate, therefore, it is doubtful what values above the average should be taken as being beyond the background variations and of significance in terms of ore bodies. Copper content, for example, was normally in the range 5-25 ppm: at four localities values of 45 ppm were obtained, at one locality a value of 50 ppm, and at another, 65 ppm. For nickel, normal values were 15-35 ppm: one locality showed 65 ppm; two, 75 ppm; and one, 175 ppm.

To set these figures in perspective, the copper content of igneous rocks ranges between 10 and about 90 ppm.

A workable copper ore would give values of about 10,000 ppm, which would be reduced to the order of a few hundred parts per million in the soil cover. The nickel content of igneous rocks ranges from about 4 ppm to more than 100 ppm; a nickel ore could give values as high as 15,000 ppm, and typical values in the soil cover might again be several hundred parts per million, depending on the distance of the sampling points from the source of the metal; in an arid environment, values generally would be expected to fall rapidly with distance.

It was hoped that reconnaissance sampling might give some indication of higher-than-average values for certain metals associated with particular rock types or suites of rocks, which could be interpreted as indicating a metallogenic province. The results obtained did not point to this, and where relatively high values were obtained, it was not clear whether they were due to the presence of a locally enriched metal facies or whether an outcrop of small veins or ore bodies was responsible.

At this stage it is not possible to distinguish between these possibilities with any certainty. Seventy-nine selected samples were reanalyzed in an attempt to discover whether the metal values represented free ions or ions adsorbed onto clay minerals, or alternatively, whether the bisulfate method employed was releasing metal ions held in the lattices of silicate minerals. The method used was to shake the sample with an aqueous buffer and dithizone; the color of the dithizone layer was then compared with standards to give "cold-extractable" copper and zinc values.

The values in general were very low, and the background of less than 1 ppm. was not detectable. The relatively higher values of 3-4 ppm actually obtained generally endorsed the anomalies shown by the standard method, which gave "total" metal. In one or two samples, values for cold-extractable metal were obtained when the total content was given as zero. This is explained by the different limits of detection of the two methods: in the total-content method, less than 5 ppm was reported as zero.

Experience has shown that values obtained by the cold-extractable method may be expected to be about 10 percent of the total content, but in view of the low overall total metal content, the fact that the cold-extractable values are close to the limits of detection renders any inference drawn from them a matter of doubt. The cold-extractable results, however, represent free metal ions, or those adsorbed onto clays and thus point to actual mineral outcrops in the vicinity. The geochemical results can therefore be said to point out certain areas of metal interest which should receive further detailed exploration combined with more in-

sensitive geochemical sampling, preferably on a grid pattern.

WADI CONCENTRATES

Heavy-mineral concentrates were obtained from 111 samples of wadi sediment by panning, in water, approximately 1 cubic foot of material.

Under the climatic conditions obtaining in most of the more humid parts of the world, a sorting action occurs when rock debris is moved by running water, and a separation of the particles takes place according to their specific gravity. Heavier grain, which would normally include minerals of economic interest, tend to collect toward the base of the sedimentary column, in pockets and stringers, close to the bedrock forming the floors of the water channels. These are known as the pay gravel or pay streak. Under the weathering regime in the Aden Protectorate, soil and rock debris are swept from the higher ground by torrential flash floods and carried down the wadis by currents of such velocity that little sorting action is able to take place. Furthermore, owing to the high permeability of the wadi sediments, surface water penetrates rapidly, with the result that such floods are checked quickly, limiting the distance of travel and the facility for sorting.

In the field, the wadi sediments generally consisted of a melange ranging in size from boulders up to 5 feet in diameter down to fine sand and silt sizes. No defined pay streak appeared to be developed; but pitting and augering in this type of material presented practical difficulties, and this point has not been thoroughly investigated. Heavy minerals in the form of black sand appeared to be associated with all grades of material, but when concentrated in the sand-size fraction, this was panned to provide a sample for laboratory examination.

The samples were examined in detail by the Mineral Resources Division of Overseas Geological Surveys, with the object of (a) ascertaining whether minerals of economic value existed in the source area and (b) assisting in interpreting the geology of the area.

The field concentrates were separated in a heavy liquid (tetrabromethane) to obtain a sink fraction free from coarse quartz and feldspar, as minerals of economic interest are normally confined to the higher ranges of specific gravity. The heavy-mineral fraction was screened through 30, 60, and 120 British Standard sieves to obtain a rough guide to the grain-size distribution and to facilitate later examination with the binocular microscope. The sized products were separated into strongly, moderately, and weakly magnetic fractions to aid mineral identification and to provide a basis for semiquantitative estimates of the heavy-mineral content. This was determined by estimating the per-

centage of every mineral in each of the four magnetic fractions and then combining the results to obtain an overall value. The fine-sand size fraction was normally used for this as it was found to give an average composition for the sample as a whole. Although the analyses were mainly concerned with the heavy minerals, a few notes were added on the light fractions which invariably contained a high proportion of fresh feldspar grains; this is to be expected in arid climatic conditions.

HEAVY-MINERAL CONTENT

In general, the heavy-mineral fractions from the wadi concentrates are silicate assemblages. Hornblende, pyroxene, and magnetite are the principal constituents and are usually accompanied by smaller amounts of epidote and garnet, scarce sphene and apatite, and traces of zircon, rutile, and tourmaline.

PRINCIPAL FERROMAGNETIC MINERALS

With the exception of samples from the *Ad Dāli* area from Cretaceous volcanic rocks and samples from Wadi Hajar and other wadis to the east which drain areas of older volcanic and sedimentary terrain, hornblende is common to abundant in almost all the concentrates. In general, it is a dark-green variety and shows prismatic faces, but a brown hornblende commonly is associated with the basaltic lavas. In some samples the hornblende is accompanied by pale-green to almost colorless tremolite-actinolite, mostly in euhedral prismatic crystals. The colorless type is most abundant southwest of Lawdar, and smaller amounts occur north of Aḥwar; it is probably of metamorphic origin in most places, and, in fact, occurs in samples with high contents of garnet.

Biotite occurs in many heavy-mineral fractions but rarely in large amounts. Samples collected between Lawdar and Al Maḥfid and from Al Maḥfid south to Aḥwar contain the highest concentrations. Muscovite is noted in two samples only, and in both is associated with kyanite; however, muscovite occurs widely in the field. Pyroxene is common and is normally either olive-green to brown augite or diopsidic augite, or green to pale-green diopside. The augite commonly occurs in fine-grained euhedral crystals, associated with other materials from volcanic rocks, and is generally of volcanic origin. Most of the diopside appears to be of metamorphic origin but the optics of the two species overlap. In the Al 'Anad-*Ad Dāli* area olive-green to brown augite is as much as 60 percent of the sample, and is present in the volcanic rocks around Ghayl Barbar in the extreme west of the Western Protectorate. It is scarce between Al Kirsh and Dār Rahbān and absent from the area east of Lawdar. In the immediate vicinity of Mūdiyyah, just east of Lawdar, however, a pale-green to colorless diopside is the major constituent. Pale- to dark-green augite is again fairly

common in the Wādī Ḥajr-Wādī al Ghabar area and scarce around Al Mukallā. In the wadis west of 'Irqah, small amounts of pale-green to colorless diopside are present, and north of Aḥwar augite is again common. Aegirine is present in samples from the Al 'Anad granite area. Orthopyroxene of about hypersthene composition occurs in several samples, but only in trace amounts except for two samples from near Bayḥān; clinopyroxene is generally absent in these concentrates.

Olivine occurs in samples containing a more mafic mineral assemblage and is commonly accompanied by particles of volcanic origin, for example, grains of olivine basalt, anorthoclase, bipyramidal quartz, and composite grains of augite and magnetite. Traces of colorless olivine are in samples from the Ad Dālī-Al Musaymīr area, from Ghayl Barbar, and from the Wādī Ḥajr area of older volcanic rocks; appreciable amounts of augite are also present. Olivine is a major constituent of a sample collected near the basalt flow north of Aḥwar and is a minor constituent throughout Wādī Aḥwar.

Magnetite and ilmenite are widespread and remarkably fresh in appearance, although the magnetite in places shows alteration to martite. Ilmenite is usually a minor constituent, but in euhedral or rounded grains, and the two minerals are often difficult to distinguish by eye. The magnetite commonly is titaniferous, and the presence of hopper faces is a characteristic feature of many of the grains.

Garnet occurs in most samples but commonly in minor amounts. It varies from pink to orange, even in the same concentrate. All grains examined in oils proved to be almandine, index of refraction about 1.80, and most were weakly to moderately magnetic; all the garnet is probably of metamorphic origin. The only concentrates containing considerable amounts of the mineral come from Wādī Huraybah and its tributaries and consist of a mixture of garnet and magnetite. A few percent of garnet is recorded from Wādī Ḥasan, between Mādīyah and Al Qulayṭah, throughout the 'Ataq-Bayḥān area, and from the Wādī Aḥwar-'Irqah area.

Epidote occurs in almost every sample and in greatest amount in the eastern half of the area. West of a line from Ad Dālī to Aden it is scarce or absent. It is common to abundant between Wādī Ḥajr and Burūm, north of Al Mukallā, and in Wādī Aḥwar.

Epidote is commonly well crystallized and in many places occurs in deep green transparent euhedral grains, but most samples contain pale-yellow to yellowish-green granular particles which have the appearance of epidotized feldspar. Some larger composite grains represent epidosite.

COMMON ACCESSORY MINERALS

Sphene and apatite are widespread, but usually in scarce or trace amounts, and seldom comprise more than 5 percent of the heavy-mineral concentrate. There appears to be an antithetic relationship between the two minerals and a sympathetic relationship with the hornblende content.

The greatest concentration occurs in the Al Kirsh area which contains a syenitic mineral assemblage. Here, the sphene, which is generally the more abundant of the two minerals, comprises as much as 15 percent of the heavy-mineral concentrate. Samples from the Al 'Anad area which contain an alkalic syenite assemblage are notably rich in apatite, as are the hornblende-rich samples from Wādī Ḥasan and Wādī Rayḥān, and from Wādī Aḥwar.

The sphene generally occurs in flattened grains which contain a large number of small inclusions but commonly show crystal faces. It may vary appreciably from pale yellow or colorless to deep orange brown. Much of the sphene may be of metamorphic origin, in particular from metamorphosed igneous rocks. This origin could also be true for the apatite, but apatite in many places occurs in perfect hexagonal prisms which may even show terminations.

Sphene concentrates, separated from samples in which this mineral appeared in different associations and in slightly different shades of color, were all found to contain minor and somewhat variable amounts of niobium and yttrium when examined by X-ray fluorescence methods. A brown sphene from near Al Qulayṭah contained the most niobium and a yellow type from Al Kirsh contained rather less, but the differences were probably not sufficiently pronounced to be of practical significance.

Zircon, tourmaline, and rutile are common accessory minerals but vary greatly in type and amount and cannot be directly related to any specific rock types. They generally occur in euhedral crystals, but in samples from sedimentary areas the grains are well rounded, abundant, and accompanied by appreciable amounts of rounded polished grains of leucoxene.

The characteristic cubic grains of goethite pseudomorphs after pyrite are common everywhere but seldom in more than trace amounts. Fresh grains were found east of Mukayrās.

OTHER MINERALS

Most of the staurolite, occurring in pale-yellow anhedral grains with distinct pleochroism, was found in a belt trending west-northwest from Wādī Haraiba to Ra's ar Rujaymah. Neither staurolite nor kyanite was found in sufficient quantity to suggest the occurrence of major kyanite or staurolite schists or gneisses. (Staurolite schists were seen in the field.)

Dolomite was found in samples from Wādī Dayqah, north of Alḥwar, and in trace amounts from a locality 14 miles east of Aṣ Surrah. The grains are well crystallized and transparent and show a pronounced rhombohedral cleavage.

Barite is present in some wadi concentrates. It is a minor constituent in samples from Wādī al Ghabar and, in larger amounts from north of Al Mukallā. Celestine was found in four samples but is not likely to be of economic interest. The mineral occurs in clusters or radiating groups of fine needles or prismatic grains which suggest either a product of subaerial weathering or possibly low-temperature vein deposits.

Fluorite was identified in four concentrates from different areas. None of the more common accessory minerals of fluorite-bearing veins was found: lepidolite, topaz, amblygonite, and cassiterite were sought but not detected.

Spinel (excluding magnetite) were present in several samples, especially those containing olivine, but as a very minor accessory. In four samples the mineral proved to be chromite (see later discussion), and one concentrate contained picotite or pleonaste.

The ilmenite in the wadi concentrates occurs in black lustrous grains which are generally fresh and little altered. Some samples, however, contain pale-yellow to brown or buff-colored nonmagnetic grains which are clearly alteration products of ilmenite and rich in titanium. These have been reported as leucoxene, and several grains examined with X-ray fluorescence show a Ti/Fe ratio about 15 times higher than ordinary ilmenite. The distinction may be significant as the mineral occurs in rounded polished grains, generally accompanying rounded grains of zircon, tourmaline, and rutile, and it is thought that these may have come from the heavy-mineral residues of former sedimentary or metasedimentary rocks.

MINERALS OF POSSIBLE ECONOMIC INTEREST

With the exception of a few magnetite sands, of negligible value in the localities recorded, the wadi samples revealed little evidence of economic concentrations of minerals. In fact, under the climatic conditions prevailing and those of the geologically recent past, there has been little sorting action by the streams and rivers, and it is unlikely that placer concentrations will be found. Economic minerals released from rich vein deposits are liable to be swamped by an influx of barren material from neighboring rocks, or lost in the general movement of waste down hill slopes and wadis. Dispersion may be accelerated by wind action; also, the sand fraction of most wadi concentrates is fine grained. These conditions may account for the fact that, although a variety of rocks was collected from

outcrops throughout the area, the mineral assemblages of samples collected from widely scattered localities are remarkably similar; differentiating one sample from another often depends on trace amounts of the less common minerals. As an illustration of this, a concentrate was taken from a very small wadi at the foot of a vein containing galena that cropped out in metamorphosed sedimentary rocks in the wadi side; the mineral assemblage, however, consisted of the usual fine-grained mixture including hornblende, magnetite, epidote, pyroxene, sphene, and apatite, and no lead-bearing minerals could be detected.

Minerals characteristic of mineralized granites are practically absent and, with the possible exception of fluorite, there seems to be no hydrothermal mineral deposits. Barite, however, occurs in a number of samples and appears to be widespread in the Wādī al Ghabar area. Small amounts of pyrite are commonplace, but in the wadi concentrates these are completely altered to goethite.

The presence of fairly large grains of monazite at Mūdiyyah and of radioactive zircon from the granite between Mukayrās and Marta'ah indicates that a further search for radioactive minerals in these areas might be worthwhile.

Traces of chromite were identified in a few samples, notably just east of Dār Raḥbān, and its presence was reflected in a relatively high chromium content of a sample taken for geochemical analysis.

Garnet constitutes a large portion of two samples from Wādī Gharish and if found in quantity this mineral would be of economic interest.

West of Lawdar and east of Mūdiyyah, well-formed crystals of titaniferous magnetite, with hopper faces, were found in abundance. They were probably derived from metamorphic rocks and their source rocks might prove of interest.

MINERAL RESOURCES

Apart from the minerals mentioned below, asbestos, barite, kaolin, talc, and tourmaline were seen. That none was of commercial interest is due to small extent or poor quality. Lignite in E.A.P. was described by Little (1925), who also recorded bauxite in E.A.P. Little's bauxite-bearing section at 'Arf ad Dik was examined, but no bauxite was recognized.

BEACH SANDS

Beach sands which on field tests appeared to be of potential interest were sampled in two areas. Results of laboratory analysis of a sample (A/B/8) from the mouth of Wādī Hajr, E.A.P., are shown in table 5.

TABLE 5.—Analysis of beach sand (sample A/B/8), Wādī Hajr, Eastern Protectorate

British standard mesh	Screen analysis, in percent	Percent heavy-mineral content (specific gravity > 2.96)
+ 60	9.3	45
— 60 + 85	8.0	60
— 85 + 120	47.4	89
— 120 + 170	36.6	96
— 170 + 240	7.6	96
— 240	1	
Total	100.0	91

The composition of the total sample, based on grain count, was:

Heavy minerals:	Percent
Magnetite	35
Ilmenite	26
Zircon	19
Rutile	4
Pyroxene	3.4
Epidote	1.3
Monazite	.6
Garnet	.5
Olivine	.2
Others	1.3
Total heavy minerals	91.0
Light minerals	9.0
Total	100.0

The ilmenite and magnetite were not counted separately, but the proportions of each were assessed by an acid leaching test. This fraction also contained a little hematite and secondary iron oxide or martite. The other heavy minerals not listed above consisted mainly of brown to blue tourmaline, with traces of sphene and hornblende and an occasional grain of staurolite.

The light fraction was mainly composed of about equal amounts of calcite and quartz.

The composition of heavy-mineral fractions from the total sample and from each screen size was shown in table 6. The ilmenite content remains fairly constant, and the magnetite content decreases with decreasing grain size. The amount of +60 and -240 material was almost negligible, and no analysis of these fractions was attempted. It can be noted that zircon content increases markedly in the finer sizes.

In summary, this material may be described as a heavy-mineral beach sand containing more than 90 percent of heavy minerals, of which about 50 percent are the useful minerals ilmenite, zircon, rutile, and monazite. It is well graded, the grains are clean and well rounded, and the content of ferromagnesian silicate minerals is small. The intrinsic value of such a

TABLE 6.—Composition of heavy-mineral fractions in beach sand, Wādī Hajr, Eastern Protectorate

Heavy minerals	Screen fractions (British standard mesh), in percent				Total sample
	+60 + 85	-85 + 120	-120 + 150	-150 + 240	
Ilmenite plus magnetite	72	72	63	41	96
Zircon	2	12	28	51	22
Rutile	3	4	5	3	4
Pyroxene	10	6	1	Trace	3.7
Epidote	4	2	6	Trace	1.4
Monazite	Trace	Trace	1	3	1.4
Garnet	1	1	3	Trace	.5
Olivine	1	2	Trace	Trace	.2
Others	2	2	1	Trace	.7
Total	100	100	100	100	100

sand, however, is small, the principal salable constituents being low-priced minerals. The contained magnetite, which probably would not be salable, is rather high, and the content of the more valuable minerals, rutile and monazite, is low. Utilization of such a sand could be considered only if large tonnages (of the order of hundreds of thousands of tons) were available.

A brief examination of the surrounding area did not suggest that any such tonnage was present near the Wādī Hajr mouth; however, the combined coastline E.A.P. and W.A.P. approaches 700 miles in length, and deposits of similar character but larger size may well exist at other places. The coastal plain is of varying width, and the winnowing effect of the monsoon winds may have a significant effect in concentrating the heavy-mineral fractions.

The second sample (A/B/10) was taken from a much larger area of dune sands on the shore of Abyan at the junction of the road from Zinjibār and the coast road to Aden. It was a light-gray medium sand, with size analysis as follows:

British standard mesh	Percent of total sample
+ 60	5.5
— 60 + 85	45.8
— 85 + 120	33.5
— 120 + 150	9.1
— 150 + 240	2.5
— 240	.6
Total	100.0

The content of heavy minerals having specific gravity greater than 2.96 was 27 percent distributed as follows:

Hornblende	Abundant.
Clinopyroxene	Common.
Pyroxene-magnetite (composite grains)	Fairly common.
Epidote	Scarcely.
Biotite	Scarcely.
Garnet	Do.
Sphene	Do.

Apatite.....	Scarce.
Olivine.....	Trace.
Tremolite.....	Do.
Magnetite.....	Do.
Basaltic hornblende.....	Occasional grain.
Muscovite.....	Do.

The light fraction consisted mainly of feldspar (mostly plagioclase) with subordinate quartz and a little biotite, calcite, and shell fragments. The grains were fresh and showed little rounding. This sample, therefore, contained only 27 percent of heavy minerals, and none of any economic interest.

BUILDING STONE

Plentiful supplies of building stone are quarried from the volcanic rock of Aden Colony. More decorative types of building stone are available in the interior of the Protectorate; some of these are of very pleasing appearance, such as certain types of porphyritic volcanic rocks, granitic rock, and blue, black, and white marbles. The source nearest to Aden is north-northwest of Labj in the Al 'Anad area, where rocks of the types mentioned, together with others such as basalt and sandstone, are available. To the east of Aden, limestone is quarried at Khanfar, Abyan.

Other major centers in the Protectorate are within reach of a varied assemblage of building stone and road metal.

COPPER MINERALS

Occurrences of copper minerals were recorded as follows:

'Irqah.—At a locality 14 miles northwest of 'Irqah, approached by a major but apparently unnamed wadi, small patches of copper carbonate, (malachite) were found in calcite veins cutting granite and schistose basement rocks. The occurrence is of no commercial importance.

Zulm Bā Tha'lab. —In the northeast sector of Zulm Bā Tha'lab, some 8 miles west-northwest of Ma'bar, Hajr, malachite was found as encrustations and small patches in serpentinized Precambrian volcanic rocks. The copper mineral is associated with hematite. Both copper and iron ore are in insignificant amounts.

Ma'bar.—About 1 mile south-southeast of the road and wadi crossing at Ma'bar, Hajr, copper associated with hematite was found in serpentinized epidiotic rock. A sample submitted for analysis contained 8 percent of copper. The hematite (specularite) forms nearly continuous lenses, generally 3-4 inches in width, in altered calcitic-limonitic veins, 2-3 feet wide. In an area of about 50 square yards, 5 such veins were recorded, all striking within a few degrees of northwest. The veins run transversely to, and are exposed in, steep sided gulleys to a depth of 3-4 feet; their continuation in

depth was not proved. The maximum exposed length of the veins was 10 feet; weathered overburden conceals their probable further extension. A greenish-blue copper mineral, considered in the field to be mainly malachite, forms encrustations upon and thin ramifying veinlets within the hematite. Further traces of copper impregnating hematite were seen over the area upon hill slopes and in wadi beds.

Laboratory examination showed the predominant gangue minerals to be andradite garnet, calcite, feldspar, and quartz. Copper minerals include fine-grained black sulfides, which X-ray examination showed to be intergrowth of chalcocite, digenite, and covellite, with green and blue oxidation products which include malachite, brochantite, and chrysocolla. The identity of the copper minerals was established by X-ray powder analysis. The abundance of andradite suggests that the rock is a contact metamorphic skarn. The copper sulfides are probably supergene, as are the malachite, brochantite, and chrysocolla, and there is no evidence as to the nature of the primary mineral which presumably gave rise to the secondary enrichment copper.

A representative portion (1 lb) of the specimen was crushed and assayed for copper, iron, and precious metals, with the following results:

Copper.....	8.86 percent
Iron.....	24.03 percent
Silver.....	68 ppm or 2.2 troy ounces per long ton
Gold.....	.2 ppm or 0.1 penny- weight per long ton

The copper content is comparatively high, but this should not be overrated since the specimen is from a narrow vein; more fieldwork is required to ascertain whether this sample is representative of the overall tenor; the silver content, at current prices, would add about 4 percent to the gross value of the ore. Other constituents indicated by X-ray fluorescence, but of no economic significance, include traces of manganese, barium, strontium, and iodine, and a slight trace of molybdenum.

Wādī al Ghabar.—At various localities in Wādī al Ghabar, mainly within 3 miles north of the Wādī al Ghabar-Mudhantyah junction, malachite was found encrusting pebbles in volcanic conglomerate and also on quartz fragments. This locality is some 12 miles southeast of Jabal ad Da'ilyah where Little (1925) reported hematite with 5 percent of copper.

Geochemical analysis proved relatively high values for copper in samples from Wādī Uimam north of Al Mukallā and from the Western Protectorate near Sanāb, Al Kīsh, and 'Alī 'Abd Allāh. With the exception of the Ma'bar occurrence, which on results

of chemical analysis merits further investigation, the traces of copper mineralization are not important in themselves. However, taken in conjunction with the finds reported by Little (1925), they may suggest the existence of worthwhile deposits, and copper would appear to be one of the more interesting possibilities in the Protectorate. On the basis of the number of known occurrences, the areas between and adjacent to Wādī Ḥajr and Wādī al Ghabar in the Eastern Protectorate may be considered favorable for more detailed examination, as possibly also the area between Al Mukallā and Wādī Ḥimam.

OTHER MINERALS

Feldspar.—Many of the numerous pegmatites which occur in basement rocks are composed mainly of feldspar, commonly in large crystals as much as 8 inches in diameter. Feldspathic bands and pegmatites sufficiently free of other minerals (such as quartz and muscovite) to be of economic interest occur in numerous localities, but their extent is not such as to warrant commercial exploitation.

Most of the coarser and more continuous outcrops are of potassic feldspar. Fragments of amazonstone were found in Wādī al Jahr, 15 miles east of Aṣ Ṣurrah, but their source could not be located.

Garnet.—Garnet is common in many of the metamorphic rocks and in feldspathic pegmatites. The variety most frequently seen is almandine, but andradite and grossularite are also recorded. Garnets of gem-stone quality were not found.

Gypsum-anhydrite.—Extensive deposits of gypsum-anhydrite of the lower and middle Eocene Rus Formation occur in the eastern parts of the Protectorate. Of these the most easily accessible is that exposed between Mayfa'ah and Rudhūm on the west of Wādī Mayfa'ah. The formation consists of massive to bedded gypsum-anhydrite interbedded with limestone. Earthy shaly horizons and chert nodules occur. Thus, the deposit is of variable quality.

Rocks of the Oligocene and Miocene Shihr Group, outcropping near the coast to the east and west of Al Mukallā, also contain horizons of gypsum, gypsaceous marls, and dolomitic limestone, together with sandstone and shales.

Experiences in Somaliland, where one of the world's largest high-grade gypsum-anhydrite deposits remains unworked within 9 miles of Berbera port, do not encourage optimism concerning exploitation of material in Aden. It may be noted that the Rudhūm deposit would provide the small amount of gypsum required in any production of portland cement.

Ilmenite.—In a tributary to Wādī Dayqah, about 5 miles west-southwest of Nūṣah, small patches of nodules

of ilmenite were found in quartz veins cutting biotite schists and gneisses. The ilmenite was too disseminated and the aggregate quantity too small to be of importance.

Iron minerals.—Iron mineralization occurs at numerous localities in quartz veins, feldspathic bands, and pegmatite dikes cutting basement rocks. No large deposits of commercial interest were found. Localities in which the more significant occurrences were seen include Al Mājil, southwest of Lawdar (magnetite); 10 miles miles east of Aṣ Ṣurrah (hematite nodules in wadi); 12 miles south of Niṣāb (magnetite); and 2 miles east-southeast of Jabal ath Thanlyah (specular hematite in quartz veins). Iron pyrites reported in Al Wāḥidī State and Wādī Jirdān ('Iyādh) is of interest only as suggesting the presence of sulfide ores.

Lead.—About 13 miles north of Aḥwar, galena occurs as imperisistent veins, about 2 inches wide, in association with partly brecciated quartz and calcite in a weathered-out fault plane cutting basement rocks. It is likely that the galena originated from low-temperature hydrothermal solutions of magmatic origin.

The fault or shear zone, which is 8–12 inches wide, strikes north across the trend of basement rocks, which here is east. Much of the more easily accessible galena has been excavated by local inhabitants, but traces of the mineral were seen over a distance of about 100 feet where the fault plane is exposed on a steep slope above a wadi bed.

The Mineral Resources Division report on a sample is as follows:

The sample consists of coarse-grained galena, apparently from a veinlet or rib from $\frac{3}{4}$ to $1\frac{1}{2}$ inches in thickness, with only a small proportion of gangue mineral, principally white calcite. A representative portion (8 oz in weight) was crushed for analysis and by a qualitative X-ray fluorescence examination was found to consist of lead, predominantly, with traces of iron, silver, copper, and zinc. Quantitative assays showed 70.8 percent of lead and 8.6 troy ounces of silver per ton of ore. These values correspond to a galena content of approximately 82 percent and 12 ounces of silver per ton of lead. At current metal prices the silver content adds only 7 percent to the gross value of the lead in the ore.

A thin crust of alteration products on the surface of the galena, largely cerussite and indeterminate ferruginous material, was shown by X-ray fluorescence examination to contain the same trace element suite as the assay sample and, in addition a trace of molybdenum. The latter is presumably present as traces of wulfenite and is probably an indication of molybdenum in the country rock rather than a primary association of molybdenum with lead.

In basement rocks of granite gneiss and schist 1 mile south of Thirah, small quantities of galena have been reported in quartz stringers and pods. These occurrences are too small to be of commercial importance.

Mica.—Muscovite is a ubiquitous constituent of the pegmatites which occur in many areas of basement

rocks. Books of muscovite were noted in the following localities.

Wādī Ḥasan: In Wādī Ḥasan about 11 miles west-southwest of Ar Rawḍah, thin books of muscovite with inclusions of garnet occur with quartz and feldspar in pegmatites cutting biotite schists. The books are about 1½ square inches in area.

Wādī Raybān: About 7 miles southwest of Al Majīl, muscovite plates and thin books of about 1 square inch in area are scattered abundantly through pegmatites.

Mūdiyyah area: Books of muscovite are abundant in pegmatites cutting granite. The books are dispersed and scattered through the dike rocks and the largest seen were about 4 square inches in area.

Four miles west of Nūṣah: Muscovite books as much as 6 square inches in area occur in a pegmatite with quartz feldspar.

Wādī 'Abadān, Niṣāb: Five miles south of Niṣāb, thin books of muscovite as much as 4 square inches in area are scattered through pegmatite dikes cutting granite. The pegmatites are 3-6 feet wide and may be as much as 30 yards long.

Sa'id: Three miles west of Sa'id, muscovite books as much as 6 square inches in area are abundant in coarse pegmatites cutting biotite schist and gneiss.

Wādī Gharīsh: About 12 miles north of Balḥāf, muscovite in books as much as 4 square inches in area, occur sporadically with quartz, feldspar, and red garnet in imperistent pegmatites (fig. 25).

Northwest of 'Irqah: About 14 miles northwest of 'Irqah, muscovite occurs in pegmatite cutting biotite-muscovite schists and granitic and feldspathized rocks. Plates as much as 10 square inches in area were seen.

The most important occurrence of mica is the last named, near 'Irqah. Here muscovite in books 4 inches thick and as much as 10 square inches in area forms a nearly continuous zone about 9 feet wide; it extends the length of a feldspar-quartz pegmatitic body, some 12 feet wide and 30 feet long, which is exposed in a steep cliff face of biotite-quartz-feldspar schist. The pegmatite trends in a direction of 230°. The zone of muscovite books extends in depth to about 9 feet and may continue to greater depths. The books of mica are arranged at all angles commonly mutually at right angles, and the plates commonly are bent and buckled; however, flat plates could be obtained. The sample submitted to the Mineral Resources Division is reported to contain small rhombs of a carbonate mineral (as inclusions in the mica plates).

In the Sa'id occurrence the presence of numerous pegmatite dikes containing abundant, though scattered, muscovite suggests that further examination might possibly disclose larger segregations of mica.

The occurrence 4 miles west of Nūṣah is close to the Mūdiyyah-Nūṣah track. The mica was seen in a pegmatite dike about 3 feet wide and 60 feet long, striking east. Again the books are arranged in a decussate manner so that plates tend to be buckled and contorted. The laboratory report states that the white muscovite plates include sporadic crystals of flattened pink garnet.

The mica seen in the Aden Protectorate is not likely to be of commercial interest, firstly because quantity is too small to warrant exploitation, and secondly because that seen in plates large enough to be of interest is generally bent or buckled and contains mineral inclusions.

Quartz.—Massive, opaque, and vitreous quartz is common in the numerous pegmatites and veins of the Protectorate. Well-crystallized forms were infrequently seen, and quartz gem stones were not recorded.

Commercial exploitation of this ubiquitous mineral depends upon an advanced state of general industrialization and is not likely to be worth consideration in the Protectorate.

Rock salt.—Deposits of rock salt are known to occur in salt domes at 'Iyādh (Hayd al Milb); Ayadim, about 33 miles west-northwest of 'Iyādh; La'i'adin (Jabel al Milb), about 38 miles N. 64° E. from an Nuqūb, Bayḥān (some 50 miles by track from an Nuqūb); Milb Kharwah, about 24 miles N. 12° E. from 'Iyādh; Milb Maq'ah, about 18 miles N. 10° E. from Shabwah; Al Minṭāq, about 5 miles N. 35° W. from Sīdārah; Ṣāfir, about 18 miles southwest of Jabal ath Thantīyah, on the Yemen border; Shabwah; Siyal al Milb, about 12 miles northwest of Sīdārah.



FIGURE 25.—Pegmatite dikes in quartzite, Wādī Gharīsh.

The salt domes at 'Iyādh, Lai'adin, and Milh Kharwah were examined and considered to be of Jurassic age; there is little doubt that the remainder are of the same age.

At Lai'adin massive rock salt is overlain by varicolored shales, bituminous in part, and gypsiferous beds. Toward the surface of the dome, salt is intermixed with fragments and blocks of contorted shale with thin lignitic lenses and bands. The gray shale is in part a paper-thin laminated variety. Well-formed salt crystals line fracture planes in brecciated shale and form stalactitic deposits under cliff faces. The bulk of the deposit is pink to white massive salt.

At 'Iyādh the elongated dome structure is very clear, the peripheral slopes consisting of thin-bedded

(lagoonal) limestone interbedded with minor calcareous shales, and evaporitic deposits of concretionary brecciated gypsum overlie salt in the central areas.

At Milh Kharwah massive rock salt forms the center of the dome and thin bands of salt are interlayered with steeply dipping dark bituminous shales. Jurassic limestone again forms the peripheral slopes.

At the time of the authors' visit salt was being worked at Lai'adin and 'Iyādh for local consumption and also for export to Yemen (fig. 26). Probably a number of the other salt deposits are similarly worked, by local labor using simple tools.

It is not thought that the present exploitation of salt deposits can be significantly increased, in view of the difficulty of access to the salt deposits, most of which



FIGURE 26.—Workers excavating salt at Lai'adin salt dome.

lie in or near the Ramlat as Sab'atayn; the poor communications to the coast; and the difficulties of marketing exported salt.

PORTLAND AND OTHER CEMENTS

The raw mix for portland-cement manufacture usually consists of about 3 parts of predominantly calcareous material (chalk or limestone) and 1 part of predominantly argillaceous material (clay, shale, or river mud). The overriding factor is the bulk composition of the available raw materials, as it is essential that these give a mix correctly balanced in terms of CaO , SiO_2 , Al_2O_3 , and Fe_2O_3 . An upper limit to the MgO content is usually set at 5 percent, as an excess may cause the formation of periclase which may result in the failure of the concrete, through slow hydration. Gypsum is normally added to the clinker at the grinding stage, to control setting time.

To make an initial assessment of the general availability of raw materials for cement manufacture, three localities, selected for easy accessibility, were sampled; these were (a) Khanfar rock, near Ji'ar, Abyan district (sample A58), (b) South-southeast of Dirjaj, compass bearing 40° to Khanfar rock (sample A267), and (c) Al Mukallā, near road to Al Khalaf police station (sample A262).

Khanfar rock: The sample was taken from a quarry in Jurassic rocks. The exposed section was of bedded dark-brown to gray crystalline limestone and porcellaneous limestone, cut by numerous thin calcite veins. The limestone was stained purple in part. Interbedded with limestone were beds about 10 feet thick of yellow-brown to gray paper shales, with ironstone concretions and much fibrous gypsum. The rocks were fractured and jointed.

Dirjaj locality: The sample was taken from Jurassic beds dipping 40° in a direction of 160° , and estimated visually as about 250 feet thick. The series consists of fossiliferous beds of pink to brown crystalline limestone, about 3 feet thick, interlayered with rubbly, shaly limestone and with marly beds about 1 foot thick. Joint and fracture planes are iron stained and numerous iron carbonate concretions are present. The base of the series is sandy limestone and calcareous sandstone, resting upon a conglomeratic quartzose sandstone some 8–12 feet thick, which in turn rests unconformably upon basement rocks. The Jurassic rocks are considered to be of the Kohlan Formation (Middle to Lower? Jurassic), with upper beds possibly of the Shuqra Formation (Upper Jurassic).

Al Mukallā: The sample was collected from Cretaceous rocks exposed in a cliff face adjoining the road from Al Mukallā to Ra's Al Mukallā, in the

vicinity of Al Khalaf police station. Cretaceous rocks of the Qishn Formation (Barremian-Aptian) here consist of variegated pink-red, yellow-brown, and white, crystalline, porcellaneous, and sandy limestone. Field observation suggests that the limestone is dolomitic, at least in part. The rock is iron stained. The Cretaceous beds unconformably upon basement rocks and are overlain by Paleocene limestones.

Results of chemical analysis of the samples from the three localities are shown in table 7.

TABLE 7.—Composition of limestones, in percent
[a.d., not detected]

Constituent	Dolomitic limestone		Argillaceous limestone
	A58 Khanfar	A262 Al Mukallā	A267 Dirjaj
CaO	35.98	33.14	34.48
MgO	14.97	18.90	2.52
SiO_2	.09	.54	22.63
Al_2O_3	.62	.32	1.20
Fe_2O_3	1.42	.26	2.45
TiO_2	a.d.	a.d.	.30
Na_2O			.40
K_2O			1.93
MnO	.30	0.5	.39
P_2O_5	.04	.09	.06
S	0.4	0.5	.07
Loss on ignition.....	45.53	46.53	26.29
Total.....	99.54	99.80	99.71

The average composition of portland-cement clinker shows a $\text{CaO}:\text{MgO}$ ratio of 44. When the raw material is particularly low in MgO the ratio may exceed 100. The ratio's lower limit is 14, at which point the MgO content of the clinker approaches the specified maximum (say 5 percent).

Samples A58 and A262 have $\text{CaO}:\text{MgO}$ ratios of about 2% and 1% respectively. They are therefore completely unsuitable for portland-cement manufacture. It is not possible to calculate a satisfactory clinker analysis from any mixture of these limestones with (a) an orthodox argillaceous material or (b) the argillaceous limestone, sample A267. In both, the MgO content would still be too high.

Sample A267 has a $\text{CaO}:\text{MgO}$ ratio of about 14. On a loss-free basis, its composition is as follows:

	Percent
CaO	48.08
MgO	3.51
SiO_2	32.96
Al_2O_3	7.25
Fe_2O_3	3.42

This composition shows a deficiency of CaO and a corresponding excess of $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$. It could be balanced to provide a reasonable portland-cement clinker composition by adding a material low in MgO and ranging from pure limestone to moderately

argillaceous limestone. By adding 120 parts CaCO_3 (pure limestone) to 200 parts of sample A267 the $\text{CaO}:\text{MgO}$ ratio increases to 27. The silica modulus (derived from the ratio of SiO_2 to combined Al_2O_3 and Fe_2O_3) is 3.1, which is rather high, the normal range being from 2.4 to 2.7. It could easily be reduced by adding iron ore to the raw mix.

The dolomitic limestones A58 and A262 could be used for making magnesian lime, which is acceptable for certain building purposes; being low in silica and alumina, the lime would have negligible hydraulic properties.

The argillaceous limestone A267 would probably give a cementitious product after burning. However, further work would be necessary to determine the performance of such a product.

It is apparent from the foregoing that in the production of portland cement considerable limitations are imposed as to the quality of materials. Economic considerations limit the distance over which raw materials may be carried, and cement works are usually sited accordingly. Thus the production of cement to specified standards, such as would be required to found an export trade or to use in structures of any importance, depends upon finding suitable limestone in an accessible place in juxtaposition with siliceous-aluminous material such as clay, shale, or mud.

The easily accessible limestones sampled are not suitable. It may be added that in calcareous sedimentary rocks of Jurassic to Oligocene and Miocene age, important dolomitic beds are known to exist; this suggests that the magnesia content of other Protectorate limestones is likely to be high. Crystalline limestones associated with the basement rocks are also dolomitic in many of the known outcrops. However, especially in the Eastern Protectorate, limestone is present in huge quantities, and it is not improbable that appropriate cement-making materials could be found reasonably close together. The question of transportation would then arise.

The search for appropriate raw material is not made easier by the fact that dolomite and dolomitic limestone are not easily recognized in the field and chemical analysis is therefore essential from the first stages of exploration. From the point of view of competitive commercial production the prospects do not appear to be good.

SUMMARY

Neither during the 1961-62 survey nor in the course of previous work have mineral deposits been found worthy of further commercial exploitation under the conditions obtaining. In this connection the prevalence of syntectonic granites and granitized rock may be

relevant, and few minerals characteristic of mineralized granites have been recorded. Clearly intrusive granite does, however, occur in several areas, and in former Somaliland Protectorate cassiterite deposits have been found in quartz veins, probably associated with intrusive granite of comparable age. Of the minerals found in the Protectorate, perhaps most interest attaches to copper. In view of the large area involved and the comparatively little exploration done, it would be premature to draw firm conclusions as to the presence or absence of important mineral deposits.

WATER RESOURCES

The Aden Protectorate lies in the so-called arid zone, which stretches from the Atlantic seaboard to the North African coast to Sind in Pakistan, with a discontinuous extension as far east as China. It cannot be properly defined on a climatic basis, but its problems are climatic in origin and stem from the imbalance between water supply and water need. The zone as a whole is characterized by wide fluctuations in precipitation, temperature, and aridity. Rainfall is infrequent, localized, irregular, and often of high intensity; it ranges from less than 1 inch to as much as 20 inches in some years. Temperatures range from freezing to above 130°F , with low relative humidity. Such factors require a high degree of specialization in plants and animals, and set the pattern of land use.

Water is the limiting factor in agriculture, on which permanent or semipermanent settlement must depend; since the time when these arid areas were first colonized the chief preoccupation has been to conserve and to put to use as much of the limited natural precipitation as possible. Archeological research has shown that many of the now-dead cities of Arabia, formerly thought to have depended entirely on the caravan trade, in fact possessed a highly developed agriculture and even evolved methods for turning the destructive forces of floods to constructive use. The decline of many of these earlier civilizations is now ascribed to political and other factors, and there is no evidence either historical, archeological, or botanical (based on the study of tree rings) to show that the climate has become significantly more arid during the historic period. Such research has proved the occurrence of drought periods, often of many years' duration, but these have not been confined to the arid zone and probably resulted from long-term climatic cycles caused by, for example, sunspot activity. It may well be that no one factor has been responsible for decline of civilizations in the arid zone. The delicacy of the balance between such societies and their environment was precarious and easily upset, and there was far less latitude of action than under other conditions;

any factor causing unbalance could be disastrous. A program of research into arid-zone problems should therefore be a detailed and integrated product of scientific research rather than a limited assemblage of facts, and the collection of data should be extended over a period broader than the known climatic cycles, that is 20-30 years. Empirical solutions based on short-term investigations may prove to be costly failures.

In the arid zone, runoff is excessive, owing to the high intensity of the rainfall, and flash floods (seil) are the result. The immediate effect of these is to sweep off the soil cover from the interfluvies into the wadis and flood plains, where it is deposited or can be artificially induced to collect. Being unleached detritus formed largely by the mechanical breakdown of bedrock, it can, depending on the parent material, provide a very fertile soil when suitably irrigated. Rainfall from a large catchment area, when concentrated in the wadis, is equivalent to precipitation increased several hundred-fold and is more than adequate for most farm crops. From the earliest times, therefore, the object of organized agriculture has been to create fields in the wadis and on the flood plains, with a controlled supply of water. Recent plans for agriculture in the Negev desert (Goldschmidt, 1961) based on spate irrigation have shown that the designs of the necessary earth-works, calculated by specialists with the latest technical aids, coincide almost exactly with those evolved in earlier times by methods of trial and error. Such designs call for the overland gravity flow of water from higher ground down to the farmland, if necessary by an elaborate system of interceptors and conveyors with regulators.

IRRIGATION PRACTICE

Agricultural techniques and the utilization of rain-water and floodwater vary according to position along a given watercourse and have a pattern with many common features in countries throughout the arid zone. In tributary wadis, many of which are steep and narrow, the water must be brought under control from the watershed down. This is done by means of dams of stone or of bushes held in position by large stones, which are built right across the wadi; where the rush of water is severe, bush dams are favored, being more pliant. The dams reduce the velocity of the water and cause deposition of soil particles, which gradually build up into flat terraces across which the water spreads and infiltrates (fig. 27).

Lower down from the watershed where the gradient flattens, these terraced fields may hold considerable amounts of water in storage and it is common in the Western Protectorate to see wells built into the stone



FIGURE 27.—Terracing with stone walls up to the watershed, Ad Dali' area.

terrace walls midway across the wadis, many incorporating a system for that particular field, or irrigation canals which are bucket fed by camel-operated lifting devices.

In main wadis where the force of floodwater is extremely strong, it cannot be stopped abruptly; here it is brought under control by diversions or deflectors. Stone dikes are built out on the contour into the wadis but not completely across them. A gap of several yards is left on one side in which a broad sloping stone spillway is constructed. The next dam downstream has its spillway on the opposite side, the effect of which is to divert the floodwater into a zigzag course which slows it down, enhancing percolation and reducing erosion.

Many of the larger wadis are dissected by stony watercourses from which only part of the floodwater can be utilized. Short stone or bush dams (replaced yearly) are built out from one or both sides into the watercourses to deflect water obliquely into artificial channels along which it is led, through regulators, to terraced fields downstream on the wadi flanks at a slightly lower level than the point of water intake (fig. 28). The height of the interceptor dams is determined by the maximum amount of water that the channels will take, and the surplus floodwater flows over the top. Water is conducted for great distances along these channels, which are built narrow and deep to reduce evaporation.

Isolated fields or interconnected groups of fields are also found on flood plains and on shallow pediments at the foot of high ground. In these places low walls



FIGURE 28.—Walled fields flanking large wadi, Aḍ Ḍālī' area.

of boulders are built obliquely up the pediments to a point on the debris slope above where the gradient is considerable (in several localities in the Western Protectorate slopes of 20° were measured). These serve to collect and channel surface runoff onto the artificial or natural fields. To supply enough water for a season's crop growth, large collecting grounds are clearly necessary; Goldschmidt (1961) gave an average ratio of 20:1 for catchment area to irrigated land.

It is only in wadis and flood plains with more than about 10 feet of alluvium that permanent or semi-permanent supplies of reasonably fresh water are to be expected, since they provide the only aquifers with possibilities of regular recharge. In the summer months when most wadis are completely dry, supplies of underground water may be found in sand bodies which are generally lenticular—isolated or interconnected—through which there may be slow downstream seepage. Such supplies are located by means of trial borings, the experience and intuition of the local people providing an important subjective factor. Where water regularly occurs near the surface, settlements have been established, linked by camel tracks. Dry wadis thus become important travel routes.

SUGGESTED METHODS FOR LOCATION AND STORAGE OF WATER SUPPLIES

In the larger wadis particularly, geophysical (resistivity) methods could successfully be applied to locate water, and small portable instruments are now available which are suitable for this purpose. Other limited supplies of water for domestic purposes and also possibly for irrigation might be obtained as required by sinking additional wells in the wadis, subject to the factors of low reserves of extractable water, mutual interference with neighboring wells, and the fact that the quality of ground water may vary considerably over short distances. Adjacent wells, in fact, often show great differences in total salinity (see "Well data" section) owing to variable wadi sediments through which the underground flow passes, and to differential rates of evaporation and concentration. Where the pattern of variability is on a large scale, geophysical (resistivity) methods could in many places be applied to define the bodies and channels of better quality water.

An obvious method of trapping and storing this subsurface water would be by means of dams based on the wadi floors. In practice difficulty arises in finding sites where the wadi floor and sides are suffi-

ently impermeable and in providing low-cost material and methods of construction in isolated areas. It would appear that there is scope for research in the matter, since this type of reservoir, being underground, would substantially reduce the loss by evaporation, which under the prevailing climatic conditions may reach, if not exceed, 50 inches a year. Another very important factor is that the increase in salinity, which results from a high rate of evaporation, is reduced. Such subsurface cutoff dams can be formed by grouting with cement or bentonite directly into the ground, or by excavating and constructing, with shuttering, a wall of cement-stabilized sandy gravel or bitumen-stabilized sand. According to the Soil Mechanics Division of the United Kingdom Tropical Building Research Station the local soils and wadi sediments would probably be suitable, and it was felt that slight losses by seepage through the wadi sides and floor could be accepted. With both these methods, however, special equipment is required and a further difficulty arises in the Protectorate in that wood for shuttering is not locally grown.

In addition to geophysical work, a study of the vegetation as seen on aerial photographs may be of great assistance in locating water and estimating its quality. Such interpretation is based on the simple premises that deep-rooting phreatophytes are in contact with a permanent supply of ground water of reasonable quality within 50-60 feet of the surface, and that the size of the vegetated area is a measure of the amount of water available. Mann (1957) gave a figure of 1 million gallons per annum as the water requirement for a 1-acre patch of phreatophytes (in his paper, the mesquite bush (*Prosopis*)). Lines of tamarisk trees and camel-thorn shrubs are common in the wadis of the Protectorate and mark the course of surface or underground water channels; they could be used as direct indicators for locating subsurface supplies of water (fig. 29). In north-central Arabia the running gourd vine, *Citrullus colocynthis* (L.) Schrad, is used by the local people as an indicator of ground water and with its aid they have been said to locate wells more than 200 feet deep (J. H. Whitney, in Dixey and Shaw, 1961). Patches of shallow-rooted xerophytes grow in silty flats in areas of pure desert, for example the Ramlat as Sab'atayn; these must subsist on near-surface moisture that probably is unconnected with the ground-water table and probably is derived from condensed atmospheric moisture. Remarkably heavy dews were noted even in this area and their effects on plant and animal life are clearly significant, if largely unknown. In such areas, the infrequent heavy rain which falls in storms appears to have a very long lasting effect on the vegetation, and is said by the Bedouin to be noticeable for a period of

years. The land surface dries out quickly after such rains and the portion of the rainfall that has penetrated the ground deeply is sealed in by the dry surface layer.

It would appear that water can only pass through this layer in the vapor phase by a process of gaseous diffusion, which is extremely slow. Measurements taken with a thermistor in the Ramlat as Sab'atayn showed that about 3 feet below the sand surface, temperatures were remarkably constant, with no diurnal fluctuations, and were relatively low—a further factor contributing to small water losses.

In the desert areas proper, newly percolated rain-water may accumulate as lenses resting on denser saline water. During the military campaigns in the Western Libyan Desert, relatively fresh water was found overlying water having a salinity of about 5,000-6,000 ppm, that is, unpotable (Shotton, in Dixey, 1956b). Such bodies of fresh water, with salinities varying from 900 to 2,000 ppm, are normally spasmodic in occurrence, only a few feet in depth, and limited in extent. When pumped, increasing salinity points to the impending exhaustion of the supply; in general, the overpumping of ground-water supplies in arid lands gives rise to increasing salinity. A few exceptions to this occur where the extracted water is replaced by newly precipitated rainfall from local or possibly distant sources. Fresh-water bodies are known from other territories, for example the Kalahari Desert, where the underground water does not seem to be replenished, and their presence has been attributed to the fact that the water is "fossil," that it accumulated in a past humid climatic period. An alternative possibility is that the water is perched; this occurs where strata such as impermeable clay beds hold water above and separate from the main water table.

WELL DATA

Along the coast between Al Mukallā and Aden a number of fishing villages are supplied by wells within half a mile of the shore. The water levels are a few feet above mean sea level and probably represent wedges of fresh water floating on sea water (Ghyben-Herzberg principle). The fresh water has probably originated partly from the higher ground behind the coastal plain by slow seaward movement, and partly from natural precipitation. Typical salinities measured were as follows:

	Total dissolved solids (ppm)
'Iraqah.....	1,300
Bi'e 'AR.....	1,600
Hijm Ba'Id fort.....	1,800



FIGURE 29.—Vegetation outlining the drainage pattern, Niṣāb area.

Water of least salinity is found in wells in wadi beds; for example, water in Wādī Merwall contains 800 ppm. Many wadis fade out in the sand dunes with a mile or so of the sea, but a flow of water continues in underground channels, the courses of which can be plotted on aerial photographs by the rough alinement of trees and shrubs.

The quality of available water is often a critical factor, major characteristics that define quality being the total concentration of soluble salts, the percentage of bicarbonates, particularly sodium, and the presence of minor elements, such as boron, which may have toxic effects. Water containing 3,000 ppm total dissolved solids can be used regularly for domestic purposes; even 5,000 ppm is acceptable for short periods. Cattle can thrive on much more saline supplies, to a maximum of about 9,500 ppm. Very high concentrations of 15,600 ppm are reportedly used for sheep in Australia (Dixey, 1956b).

For irrigation the safe upper limit is considered to be about 700 ppm, although higher concentrations of certain salts could be accepted for particular crops. The

suitability may thus depend as much on the proportions of the constituent ions as on their total concentration; a limiting factor is the presence of alkaline carbonates or bicarbonates, which give rise to an unfavorable soil condition (the so-called black alkali soil). At least partial chemical analyses to determine the Cl, SO₄, and HCO₃ anions should be made to show the main characteristics of the ground water, and, particularly when the water is used continuously for irrigation, such analyses should be done as a routine practice to detect any progressive changes in chemical composition. Because the proportion of solutes increases in the soil by evaporation and may cause precipitation within the solum, efficient drainage must be combined with irrigation schemes or saline soils will result, with unfavorable crop response.

In general, ground water in the Western Protectorate was not found to be excessively saline. Domestic water from shallow wells 30–60 feet deep was normally in the range 900 ppm (Lawdar) to 400 ppm (ad Ḍālī; Al Fajarah). Wells in the larger wadis often showed surprisingly low salinities. On theoretical grounds the

mineralization of water would be expected to increase with distance from its source by the passage through progressively larger volumes of alluvium and by concentration through evaporation. In Wādī Bayḥān, however, at the town of Bayḥān a salinity of only 230 ppm was recorded; other figures were 550 ppm at Sa'id and 900 ppm at Mayfa'ah. The quality of the water, particularly in the major wadis, is often variable, however, owing to the fact that several bodies or channels of water exist. Two wells in Wādī Durā, which is almost 3 miles wide west of the town of Niṣāb, gave readings of 800 ppm (old fort) and 1,700 ppm (political officer's house); the wells were about 400 yards apart. A sample from the latter well was titrated with silver nitrate and gave a figure of 550 ppm sodium chloride equivalent. It may be noted here that in the Abyan delta salinities also vary widely within short distances.

Some 24 miles west of Niṣāb, water from an 18-foot well in the fort at Khawrah had a salinity of only 500 ppm. Between the watershed east of Khawrah and Niṣāb is a large area (covering 25-35 sq mi) of apparently good agricultural land that could be very satisfactorily irrigated with water of this quality. Similarly, it was clear from the aerial photographs that Wādī Markhah, which runs parallel with Wādī Durā some 15 miles to the north, forms a very much larger area of comparable geologic background and, consequently, similar parent soil material; it also has a much greater volume of ground water owing to its greater length and catchment area. Wādī Markhah was closed for security reasons and was not visited by the authors.

At 'Ataq, on the edge of the sand desert, three wadis converge and the depth of alluvium is about 100 feet. The yield of water is generally low and has fallen over the last few years, but its quality is good, ranging from 650 to 850 ppm in the four wells at 'Ataq and nearby. A certain amount of drilling was done here by Service units to locate wells for supplying the military base, but although sited in the wadis or close to them, these boreholes failed to locate fresh supplies. As there are no surface geologic features to indicate where the underground water channels may lie, resort must be had to geophysical methods, and it has already been shown that resistivity can be used successfully under similar conditions in Wādī Ḥaḍramawt (S. H. Shaw, unpub. data, 1952). Twenty-five miles north of 'Iyādh, on the southern fringe of the Ramlat as Sab'atayn, the ground water was found to be of even higher quality, namely 100 ppm. Highly mineralized water might have been expected instead, because the 'Iyādh well lies in Wādī Jirdān which draws its water from the limestone jol to the east, where gypsaceous beds are numerous.

PROSPECTS

Presumably, possibilities exist for finding water in the area of desert to the west, in the Jaww Kudayf and the Ramlat as Sab'atayn, because many wadi courses extend for several miles into them from the Niṣāb-Bayḥān mountains on the south and the limestone jol in the east. The most outstanding example observed is Wādī Bayḥān, which can be traced at least 45 miles into the desert, as far as Al 'Ubaylāt. It is well marked on the ground, although the wadi floor is not level and is obstructed at many points by sand dunes. No record of data of the last flood to reach Al 'Ubaylāt could be obtained, but to the west of the present wadi, broken lines of trees now partly submerged in sand indicated that the course of the wadi had moved progressively to the east with the prevailing wind. Separating the hill known as Faridah from the southern end of the main ridge of Jabal alī Thanyah is a wide, shallow wadi containing gravel banks and small boulders of quartzite. This is reputed to be Wādī al Abrād which, according to Philby (1938), rises in the Yemen mountains more than 50 miles to the west, the ancient city of Ma'rib being on one of its tributaries.

Flood water which percolates below the level of ground affected by evaporation would presumably remain available, although at considerable depths, probably in excess of 150 feet. Well-defined permanent wadis would be expected to carry a slow underground flow past the point where they cease to be recognizable as wadis at the surface. This water may even add to a permanent ground-water table at depth beneath the desert, although if such exists it is probably saline as a result of concentration by slow upward diffusion of water vapor. If geophysical work is undertaken in the 'Ataq area, the hydrologic conditions at the mouths of the larger nearby wadis should be investigated. Here outwash fans of various types are common, parts of which consist of silt or silty sand. These could be walled and used for agriculture if water were available.

GAZETTEER

Degrees of latitude and longitude are given to the nearest minute. The coordinates given for wadis indicate the general location of the principal references in the text.

	Latitude (N.)	Longitude (E.)
Abyan delta.....	13°07'	45°22'
Ad Dali'.....	13°42'	44°44'
Aden.....	12°46'	45°02'
Alḥwar.....	13°32'	46°43'
Al 'Amd.....	13°16'	44°45'
Al Fajarah.....	12°59'	44°19'
Al Huḡayrah.....	14°25'	46°28'
Al Uḡfān.....	14°42'	46°30'
Al Khabr.....	14°06'	47°05'

	Latitude (N)	Longitude (E)		Latitude (N)	Longitude (E)
Al Kirsh.....	13°22'	44°30'	Nigab (Angab).....	14°31'	46°20'
Al Majil.....	13°50'	45°47'	Nqah.....	14°00'	46°43'
Al Maḥḥid.....	14°02'	46°55'	Ra's ar Rujaymah.....	48°07'	48°45'
Al Maḥḥin'.....	13°20'	45°18'	Ra's Fartak.....	15°38'	52°14'
Al Mukalla.....	14°32'	49°07'	Ra's Ḥuṣayyah.....	14°12'	48°50'
Al Musaymir.....	13°26'	44°37'	Ra's 'Imrān.....	12°44'	44°44'
Al Qunaytah.....	13°58'	46°43'	Ra's Majdahah.....	13°59'	48°28'
Al 'Ubaylāt.....	15°09'	46°23'	Ra's Muwayyah.....	14°09'	48°48'
'Alī 'Abd Allāh.....	12°46'	44°02'	Ra's Sharwayn.....	15°20'	51°40'
An Naḡr.....	15°29'	47°00'	Ra's Quṣay'ir.....	14°55'	50°20'
An Nuḡūb.....	14°58'	45°48'	Rudhūm.....	14°04'	47°40'
Arayn.....	15°36'	46°44'	Sā'ir.....	15°40'	46°07'
'Arf ad Dik (jebel).....	14°22'	48°31'	Sa'Id.....	14°20'	46°52'
Ar Rawḡah.....	13°29'	45°30'	Sanāb.....	13°49'	44°43'
As Sawād.....	13°29'	45°34'	Shabwah.....	15°22'	47°01'
Ash Shatt.....	12°54'	44°01'	Sharkhāt.....	15°09'	51°02'
As Sufal.....	14°18'	47°02'	Shuqrāh.....	13°21'	45°42'
Aṣ Ṣurrah.....	13°57'	46°14'	Sidarah (Sidara).....	14°30'	48°05'
'Ataq.....	14°31'	46°40'	Thawr al Bahā.....	13°11'	44°18'
'Awābil.....	13°50'	44°52'	Thirah.....	13°55'	45°48'
Baḥāf.....	13°58'	48°10'	Wādī 'Abādān.....	14°30'	46°28'
Bayḥān (Bayḥān al Qasab).....	14°49'	45°44'	Wādī Abwar.....	13°39'	46°38'
Bi'r 'Alī.....	14°01'	48°21'	Wādī al Ghabar.....	14°13'	48°48'
Burūm.....	14°21'	48°57'	Wādī al Jāhr.....	13°58'	46°32'
Dār Raḥbān.....	12°52'	44°03'	Wādī al Jif'iyah.....	15°00'	45°57'
Dirjāl.....	13°16'	45°21'	Wādī al Kayf.....	13°17'	44°35'
Ghayt Barbar.....	12°50'	43°57'	Wādī Ba'Arrāb.....	14°09'	48°48'
Ḥabbān.....	14°19'	47°07'	Wādī Banā.....	13°23'	45°16'
Ḥim Ba'Id.....	13°33'	46°58'	Wādī Dār.....	13°16'	44°32'
Ḥim Murād.....	12°40'	43°30'	Wādī Dayqah.....	13°47'	46°39'
'Iraqh.....	13°38'	47°20'	Wādī Durā.....	14°26'	46°22'
'Iyādh.....	14°58'	46°48'	Wādī Gharlah.....	14°08'	48°11'
Jabal ad Da'iyah.....	14°26'	48°36'	Wādī Ḥabbān.....	14°18'	47°02'
Jabal al Birkah.....	12°42'	44°22'	Wādī Ḥajr.....	14°14'	48°33'
Jabal al Munif.....	13°17'	44°51'	Wādī Ḥasan.....	13°24'	45°27'
Jabal ath Thanlyah.....	15°48'	46°19'	Wādī Ḥimam.....	14°40'	49°08'
Jabal Jahnum.....	14°12'	48°35'	Wādī Jadin.....	12°49'	44°11'
Jabal Jihāf.....	13°45'	44°41'	Wādī Jirdān.....	14°58'	46°48'
Jabal Kharaz.....	12°44'	44°10'	Wādī Markhah.....	14°38'	46°14'
Jabal Kuwah.....	12°42'	43°30'	Wādī Maḥārif.....	14°56'	46°24'
Jabal Marāf.....	12°40'	44°25'	Wādī Mayfa'ah.....	14°08'	47°36'
Jabal Samama.....	12°42'	44°20'	Wādī Miḥ.....	13°47'	45°43'
Jabal Suwayyah.....	14°09'	48°14'	Wādī Rayḥān.....	13°37'	45°39'
Jabal Zūlm Ash Shaybah.....	14°10'	48°50'	Wādī Raymah.....	14°11'	48°37'
Jawl Aṣ Ṣalab.....	14°23'	46°40'	Yashbum.....	14°17'	46°56'
Jf'ār.....	13°13'	45°19'	Zinjibār.....	13°07'	45°23'
Jihāl al Aswad.....	14°26'	47°44'	Zūlm Bā Th's'lab.....	14°17'	48°23'
Jihāl an Nistiyin.....	14°48'	46°08'			
Jilla (Jif'ah).....	14°00'	48°07'			
Jirāl.....	12°23'	48°22'			
Karīf Shawrān.....	14°01'	48°22'			
Kawr al 'Awādhil (area).....	13°58'	45°52'			
Khanfar.....	13°13'	45°19'			
Khawrah.....	14°27'	46°08'			
Lahj.....	13°03'	44°53'			
Lawdar.....	13°53'	45°53'			
Ma'har.....	14°15'	48°33'			
Marta'ah.....	14°08'	45°55'			
Mayfa'ah.....	14°14'	47°32'			
Minād.....	13°48'	44°45'			
Mūdiyah.....	13°54'	46°03'			
Mukayras.....	13°56'	45°41'			
Musayn'ah.....	15°04'	50°38'			

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APPENDIX

AGE DETERMINATION RESULTS

By N. J. SKELLING¹

Recent work in Aden Protectorate and Somalia (former Somaliland Protectorate) has revealed marked similarities in the Precambrian geology of these terrains. In both regions the basement rocks have been subjected to two episodes of metamorphism, the first of which was the more intense, conditions reaching those of the amphibolite facies, and in parts of Somalia, the granulite facies. For convenience this episode is referred to as katametamorphism. The second metamorphism was generally of much lower grade, only locally reaching the conditions appropriate to the amphibolite facies, and with mainly dynamic effects much in evidence. This episode is referred to as epimetamorphism. Present in both regions are low-grade metasedimentary rocks comprising the Ghabar Group of the E.A.P. (Beydoun, 1960) and the Inda Ad Series of Somalia. The relationship of these formations to the crystalline basement rocks is obscure, although the evidence favors an unconformable relationship between the Somalia basement rocks and the Inda Ad Series.

Several phases of plutonic igneous activity can be distinguished. In both regions the katametamorphism was accompanied by the development of autochthonous and parautochthonous granites (the syntectonic granites of Greenwood in Aden Protectorate and the synkinematic granites of Warden in Somalia), and the later epimetamorphism was followed by the intrusion of posttectonic granites that have sharp crosscutting contacts and well-defined thermal aureoles. In Aden Protectorate, Greenwood has distinguished a group of granites which are later than the katametamorphism but earlier than the epimetamorphism, which he terms the intertectonic granites; in Somalia, Daniels, Skiba, and Sutton (1963) have described a group of layered gabbroic intrusions which also postdate the katametamorphism and predate the epimetamorphism. These layered mafic intrusions are of particular importance in that they indicate a long time interval between the two metamorphisms in Somalia. Thus in some localities well-defined thermal aureoles have been observed adjacent to the gabbros, indicating that the country rocks had time to cool after the early katametamorphism, whereas

the banded nature of these mafic rocks indicates the slow accumulation of crystals by gravity differentiation, which could only occur during a long period of quiescence.

TABLE 8.—Age determinations from former British Somaliland and Aden Protectorate

(In calculating the K-Ar ages the following constants were used:

$$^{\circ}\text{K} \lambda_0 = 4.77 \times 10^{-11} \text{ yr}^{-1}$$

$$\lambda_e = 0.564 \times 10^{-10} \text{ yr}^{-1}$$

Determination No.	Nature and location	Potassium (per cent)	⁴⁰ Ar/ ³⁹ K ratio	Age (m.y.)
Former British Somaliland				
OGS. 62.30.....	Biotope from Dajmoleh granulite series. Lat 10°59' N., long 47°02' E.	7.73	0.0331	405±25
51.....	Muscovite from garnet-muscovite gneiss. Near Bawn. Lat 10°12' N., long 47°02' E.	7.22	0.015	500±30
45.....	Biotope from biotite-adamellite intrusive into basement rocks and the Inda Ad Series. Near Wadi. Lat 10°50' N., long 47°12' E.	7.57	0.037	500±25
44.....	Biotope from Laa Bar granite, post-Inda Ad Series.	6.94	0.046	515±25
42.....	Whole rock "metamorphosed argillaceous sandstone" 1A5A, Inda Ad Series. Map sheet 4.	2.86	0.0355	505±25
45.....	Whole rock "sandstone" 1A5.47, Inda Ad Series. Map sheet 4.	1.05	0.043	380±40
Aden Protectorate				
63.12.....	Biotope from the Ra's Burūm granite, sample A.257.	7.47		415±25
62.53.....	Biotope from Wadi Ghabar granite, sample 246.	6.55	0.0363	360±30
52.....	Biotope from Wadi al Jifrah granite, sample 201.	7.73	0.0375	530±30
63.11.....	Biotope from Wadi Kayh granite, sample A.39.	6.57		475±30
62.53.....	Biotope from biotite-quartz schist, Wadi Kayh, sample A.70.	7.01	0.0337	505±25
63.13.....	Biotope from staurolite-garnet-mica schist, Wadi Oharib, sample A.229.	6.85	0.0429	620
61.39.....	Muscovite from quartz-muscovite dike, isolated, basement outcrop, Ra's Shawayn.	8.59	0.010	470±30

¹ A corrected determination gives an apparent age of 575±25 m.y. and a ⁴⁰Ar/³⁹K ratio of 0.0394.

New age determinations on rocks from Somalia and the Aden Protectorate are given in table 8. Most of the determinations were made on samples submitted by geologists of the former Geological Survey of Somaliland Protectorate and of the Overseas Geological Surveys. Determinations were all made by the potassium-argon method which, on the basis of past experience, has proved of greatest value to reconnaissance studies of geologically little known areas. Argon was determined by the isotope-dilution method, by using a bakeable all-glass vacuum system and a Reynolds-type glass mass spectrometer. Potassium

¹ Of the Overseas Geological Surveys.

was determined by means of an El flame photometer by direct comparison with standard solutions.

Probably the most important of these new age determinations are those on the Las Bar, Ra's Burūm, and Mait granites. These are all clearly posttectonic bodies having crosscutting contacts and thermal aureoles. The similarity of the determinations strongly suggests that they date the time of intrusion. In terms of current estimates of the geological time scale these granites are of Late Cambrian age. In E.A.P. the Ra's Burūm granite intrudes older volcanic rocks (see Greenwood, 1961, pl. 1); in Somalia the Las Bar granite intrudes metasedimentary rocks of the Inda Ad Series, and the Mait granite cuts both regionally metamorphosed basement rocks and members of the Inda Ad Series. Thus in Somalia the basement gneisses and apparently overlying Inda Ad Series are Cambrian or older, as are the two metamorphic episodes recognized in the region. Little more can be said about the actual ages of these metamorphisms, but it is reasonable to suggest that the epimetamorphism in the basement rocks and the dynamic metamorphism which has affected the Inda Ad Series are one and the same event. Attempts to date this event by making whole-rock potassium-argon determinations on the argillaceous metasedimentary rocks of the Inda Ad Series were unsuccessful. Both determinations shown in table 8 give ages younger than those given by cross-cutting granites, and obviously the metasedimentary rocks have lost argon.

The Ra's Burūm granite of E.A.P. is unaffected by the movements that deformed metasedimentary rocks of Wādī al Ghabar, movements which can probably be correlated with the epimetamorphism of the older basement assemblage. Thus the crystalline basement rocks and the metasedimentary and older volcanic rocks of E.A.P. are also Cambrian or older.

In Aden Protectorate an earlier intrusive phase appears to be represented by the Wādī al Ghabar and Wādī al Jifīyah (Baybān) granites, dated at 560 and 550 m.y., that is, of Middle Cambrian age. These are also posttectonic granites and as such set a younger limit to the epimetamorphism. An even later intrusive episode may be represented by determinations OGS.61.39 and OGS.63.11; these ages are Ordovician.

Three determinations on micas from basement rocks from Somalia and Aden Protectorate give ages ranging from 505 to 620 m.y. From the geochronological point of view it can be postulated that two types of mica are present in the metamorphosed basement rocks; those formed during the earlier katametamorphism, and those formed during the subsequent epimetamorphism.

However, as it is known that micas, and particularly biotites, lose argon fairly readily when metamorphosed, the ages as determined on the earlier micas can be expected to have been affected by the epimetamorphism. Their apparent ages are likely to be significantly lower than their true age—that is, the time of the epimetamorphism. The best estimate of the time of the katametamorphism is given by the greatest apparent age, which is about 600 m.y., in both Somalia and Aden Protectorate. The katametamorphism is thus older than 600 m.y.

Age determinations on the later micas ideally give the age of the epimetamorphism, which on the basis of the determinations made on the posttectonic granites, must be older than 515 m.y. and is probably older than 560 m.y.

Unfortunately this simple pattern can be complicated by natural argon leakage. Such argon loss does not normally appear to exceed about 10 percent, but even this would result in an apparent age some 50 m.y. too young. This may explain the apparently anomalous results of 505 m.y. given by the biotite from the Wādī Raybān mica schist, OGS.62.53.

Definite conclusions are not justified on the basis of the few age determinations so far made from the basement rocks of these areas, but as already suggested, the katametamorphism is almost certainly older than 600 m.y., whereas the epimetamorphism probably occurred between 560 m.y. and 600 m.y.

TABLE 9.—Age determinations on biotites from the Eastern Desert, United Arab Republic

[All except determination B.3611 are from Oghthi (1961). Determination B.3611 is from Hurley and others (1958, p. 97). Monazite from what appears to be the same granite mass gives discordant ^{40}Ar ages as follows: $^{40}\text{Ar}/^{39}\text{Ar}$, 307 m.y.; $^{40}\text{Ar}/^{37}\text{Ar}$, 259 m.y.; $^{40}\text{Ar}/^{39}\text{Ar}$, 465 m.y. See Schürmann and others (1960, p. 100).]

Determination No.	Nature and location	Potassium (per cent)	$^{40}\text{Ar}/^{39}\text{Ar}$ ratio	Age (m.y.)
B.3708.....	Pink granite, late Oghthian intrusive rock, just west of Gebel Nūgrat, Lat. 24°40' N., long. 34°32' E.	3.98	0.0806	460
3725.....	Pink granite, late Oghthian intrusive rock, Wādī Essel, south of Qomel, Lat. 24°55' N., long. 34°13' E.	5.00	0.0872	540
3711.....	Gray oligoclase granite believed to be the earliest phase of the Oghthian granites, 7 km south of Gebel Muṣṣiḥ, Lat. 24°50' N., long. 34°01' E.	5.67	0.0900	520
3728.....	Same nature as for B.3711, Wādī Abū Ḥarī, Lat. 24°38' N., long. 34°39' E.	5.50	0.0965	435
3716.....	Granite gneiss, Hadāf mine area, Lat. 24°50' N., long. 34°30' E. From the core of a domal structure believed to be early Proterozoic in age.	4.85	0.0832	510
3719.....	Biotite gneiss, Hadāf mine area, Lat. 24°50' N., long. 34°30' E. This rock overlies a series of gneisses and gneiss which in turn overlies the granite gneiss of B.3716.	6.92	0.0902	455
3611.....	Dark granite from Wādī Hawāshī, Oghthian.	5.8		620

TABLE 10.—Age determinations on micas from Arabia

[Sample numbers and locations given by Aldrich and others (1960, table 11, fig. 9). Determinations also shown by Brown and Jackson (1960, fig. 1)]

Sample No.	Location	Rb-Sr 1	K-Ar
6.....	1.....	1070	710
2.....	2.....	1090	745
8.....	3.....	960	500
11.....	4.....	530	
9.....	5.....	750	
2.....	6.....	600	

¹ These are the ages obtained if a half life of 5.0×10^{10} yr. is assumed for the decay of ⁸⁷Rb. To obtain the age on the basis of a half life of 4.7×10^{10} yr. multiply by 0.94.

Regarding comparison with other regions, age determinations from Egypt and other parts of the Arabian shield are given in tables 9 and 10. As described by Brown and Jackson (1960) the main mass of the Arabian shield in western Saudi Arabia appears to have much in common with Aden Protectorate and Somalia. Brown and Jackson recognized at least two major gneissic belts which intersect at right angles beneath the Sahl Rakkab. According to these authors, one belt, which extends northeastward from the Red Sea rift, has features of injection and migmatization and is flanked by a retrogressively metamorphosed group of mafic igneous rocks, slate, and quartzite, which they considered to be near the base of the Arabian geologic column. The other belt extends northeastward and has the characteristics of orthogneiss.

Determinations on micas from synkinematic granulites and related rocks give Rb-Sr ages of about 1,000 m.y., whereas determinations on micas from somewhat younger batholiths and stocks of calc-alkalic granites and quartz diorites, which display both concordant and discordant features, give Rb-Sr ages of 750 and 880 m.y. Still younger ages of 600 and 530 m.y. were also reported, the former on a mica from a "younger red intrusive" rock and the latter on a mica from an unmetamorphosed granite ring dike east of At Tā'if. If these last two ages are recalculated using the Rb⁸⁷ half life of 4.7×10^{10} yr (the value preferred by the writer), one gets ages of 565 and 500 m.y.

Probably the most important feature of these determinations, and one which was not mentioned by Brown and Jackson (1960), is that where both Rb-Sr and K-Ar ages have been determined the results are discordant (see table 10). Such discordance is generally accepted as being indicative of a metamorphism after initial crystallization. This later metamorphism probably is approximately the same age as the youngest K-Ar apparent age, which is 600 m.y., particularly as there occurs in the same area the unmetamorphosed granite ring dike east of At Tā'if which gives an age about 500 m.y. (depending on the decay constant used

in the age calculation). It thus appears that the crystalline gneisses and granitic rocks in regions stretching southwestward from Jiddah on the coast toward the border of Saudi Arabia and Yemen were subjected to two metamorphic episodes: the first, at about 1,000 m.y., was followed by the intrusion of granites which in turn were followed by a second and probably milder metamorphism between 600 and 500 m.y. By analogy with results from the Aden Protectorate, where post-tectonic granite has been dated at 560 m.y., it may be suspected that the later metamorphism occurred in earliest Cambrian or latest Precambrian times.

Although Brown and Jackson made no reference to features in the basement gneisses and granites which could be indicative of polymetamorphism, the fact that the various low-grade metasedimentary and meta-volcanic rocks, such as the Fatima Formation, have been subjected to mild mainly dynamic metamorphism and rest disconformably on basement gneisses and schists, implies more than one diastrophism; it is unlikely that the basement rocks, on which the low-grade metamorphic formations rest, would be unaffected by the later diastrophism. In fact, the age determinations indicate that these rocks were affected.

Age determinations from Egypt and the northern Sudan are given in table 9. The ages are quite reminiscent of the dates determined from Somalia and Aden Protectorate. It is difficult to correlate these ages with the geologic succession proposed by Hume and Schürmann; the Gattarian granites give apparent ages ranging from 630 to 460 m.y. whereas gneisses from what were considered to be the oldest of the crystalline basement rocks give Paleozoic ages well within the apparent age span of the Gattarian granites.

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GEOLOGY OF THE ARABIAN PENINSULA

Sedimentary Geology of Saudi Arabia



Geology of the Arabian Peninsula

Sedimentary Geology of Saudi Arabia

By R. W. POWERS, L. F. RAMIREZ, C. D. REDMOND, and E. L. ELBERG, JR.

GEOLOGICAL SURVEY PROFESSIONAL PAPER 560-D

*A review of the sedimentary geology of
Saudi Arabia as shown on USGS Miscellaneous
Geologic Investigations Map I-270 A, "Geologic
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FOREWORD

This volume, "*The Geology of the Arabian Peninsula*," is a logical consequence of the geographic and geologic mapping project of the Arabian Peninsula, a cooperative venture between the Kingdom of Saudi Arabia and the Government of the United States. The Arabian-American Oil Co. and the U.S. Geological Survey did the fieldwork within the Kingdom of Saudi Arabia, and, with the approval of the governments of neighboring countries, a number of other oil companies contributed additional mapping to complete the coverage of the whole of the Arabian Peninsula. So far as we are aware, this is a unique experiment in geological cooperation among several governments, petroleum companies, and individuals.

The plan for a cooperative mapping project was originally conceived in July 1953 by the late William E. Wrather, then Director of the U.S. Geological Survey, the late James Terry Duce, then Vice President of Aramco, and the late E. L. deGolyer. George Wadsworth, then U.S. Ambassador to Saudi Arabia, and Sheikh Abdullah Sulaiman, then Minister of Finance of the Government of Saudi Arabia, lent their support to the plan. In November of the following year, 1954, Director Wrather approved the U.S. Geological Survey's participation and designated G. F. Brown responsible for the western Arabian shield region in which he had previously worked under U.S. foreign-aid programs. In January 1955 F. A. Davies, Chairman, Board of Directors, Arabian-American Oil Co., approved Aramco's participation and appointed the late R. A. Bramkamp, chief geologist, responsible for compilation of the area within the Kingdom where the sediments crop out. This responsibility fell to L. F. Ramirez following the death of R. A. Bramkamp in September 1958.

R. A. Bramkamp and G. F. Brown met in New York in February 1955 and planned the program, including scales of maps, areas of responsibility, types of terrain representation, and bilingual names. Thus there was established a cooperative agreement between the Kingdom of Saudi Arabia, the U.S. Department of State, and the Arabian-American Oil Co. to make available the basic areal geology as mapped by Aramco and the U.S. Geological Survey.

The agreement specified publication of a series of 21 maps on a scale of 1:500,000, each map covering an area 3° of longitude and 4° of latitude. Separate geologic and geographic versions were to be printed for each of the quadrangles; both versions were to be bilingual—in Arabic and English. A peninsular geologic map on a scale of 1:2,000,000 was to conclude the project.

High-altitude photography, on a scale of 1:60,000, of the Kingdom of Saudi Arabia was initiated during 1949 by the Aero Service Corp. and completed in 1959. Both third-order vertical and horizontal control and shoran were utilized in compiling the photography. This controlled photography resulted in highly accurate geographic maps at the publication scale which then served as a base for the geologic overlay. The topography of the sedimentary areas was depicted by hachuring and that of the shield region by shaded relief utilizing the airbrush technique.

The first geographic quadrangle was published in July 1956 and the last in September 1962. While preparation of the geographic sheets was in progress, a need arose for early publication of a 1:2,000,000-scale peninsular geographic map. Consequently, a preliminary edition was compiled and published in both English and Arabic in 1958. The second edition, containing additional photography and considerable new topographic and cultural data, was published in 1963. The first of the geologic map series was published in July 1956 and the final sheet in early 1964. The cooperative map project was completed in October 1963 with

the publication of the 1:2,000,000-scale "Geologic Map of the Arabian Peninsula" (Miscellaneous Geologic Investigations Map I-270 A).

As work on the quadrangles progressed, geologist, companies, and governments working in areas adjacent to the Kingdom of Saudi Arabia were consulted by Aramco and invited to participate in the mapping project. The number of cooperating participants was expanded to 11, which included the operating oil companies in the peninsula and which are identified elsewhere in this text; the Overseas Geological Surveys, London; the Government of Jordan; F. Geukens, who had worked in Yemen; and Z. R. Beydoun, who had studied the Eastern Aden Protectorate. With the close cooperation of the authors, the new data were added to data already plotted on the base map of the Arabian Peninsula.

As the geological coverage of the peninsular map grew, the need for a text to accompany the map became apparent to both the U.S. Geological Survey and the Aramco geologists. Exploratory conversations were begun by Aramco with companies working in the other countries of the Arabian Peninsula for their participation in the preparation of a monograph on the geology of the Arabian Peninsula. Each author prepared a description of the geology of the area for which he was responsible, as shown in the sources of geologic compilation diagram on the peninsular map. The U.S. Geological Survey undertook the publishing of the volume as a professional paper, and the Government of Saudi Arabia was to finance its printing. It was early agreed that there would be no effort to confine the contributions to a standard format and that no attempt would be made to work out an overall correlation chart other than shown on the "Geologic Map of the Arabian Peninsula." Thus, the individual style of authors of several nationalities is preserved.

Cooperation and relations have been of the highest order in all phases of the work. The project would not have been possible without the full support of the U.S. Department of State, the Kingdom of Saudi Arabia, and all contributors. In fact, the funds which made publication of this volume possible were contributed the Saudi Arabian Government.

The data provided by the maps and in the professional paper provide information for an orderly scientific and economic development of a subcontinent.

O. A. Seager

O. A. SEAGER,
Arabian-American Oil Co. (Retired).

W. D. Johnston, Jr.

W. D. JOHNSTON, JR.,
*Former Chief, Foreign Geology Branch,
U.S. Geological Survey.*

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GEOLOGY OF THE ARABIAN PENINSULA

SEDIMENTARY GEOLOGY OF SAUDI ARABIA

By R. W. POWERS, L. F. RAMIREZ, C. D. REDMOND, and E. L. ELBERG, JR.¹

ABSTRACT

Systematic mapping of the sedimentary geology of Saudi Arabia by Arabian-American Oil Co. (Aramco) began in 1933. By 1959, exploration parties of one type or another had surveyed more than 1,300,000 square kilometers (500,000 square miles) of sedimentary outcrop.

The foundation for sedimentary deposition is the Arabian Shield—a vast Precambrian complex of igneous and metamorphic rocks that occupies roughly one-third of the Arabian Peninsula in the west and crops out sporadically along the southern coast. Since the outset of the Paleozoic Era the shield has been amazingly stable, subject only to gentle, epeirogenic movement. On this rigid land mass was deposited an aggregate total of nearly 5,500 meters (18,000 feet) of sedimentary rocks ranging in age from presumed Cambrian to Pliocene(?).

Paleozoic, Mesozoic, and lower Tertiary strata are magnificently exposed in central Arabia where they crop out in a great curved belt bordering the shield. Here the landscape is dominated by a series of essentially parallel west-facing escarpments, each supported by a resistant limestone cap. Exposures are unusually good, and many rock units can be traced without significant interruption for 500 to nearly 1,000 km. Beds reflecting buried basement configuration dip gently and uniformly away from the escarpment region into the Persian Gulf and Rub' al Khali basins.

East of the escarpment belt is a broad expanse of relatively low-relief terrain in which Tertiary and younger deposits effectively mask older units. Clues to the character of pre-Tertiary rocks in this large area, which includes the Rub' al Khali desert and most of northeastern Arabia, are afforded only by widely scattered bore holes and oil wells.

In extreme northwestern Arabia, largely lower Paleozoic sedimentary rocks are exposed, although a basinal area bordering the Paleozoic rocks on the north is characterized by thick Upper Cretaceous to Tertiary strata. Tertiary to Recent volcanic rocks cover substantial parts of the area.

In general the older sedimentary rocks are exposed in north-central and northwestern Arabia near the Precambrian basement where as much as 2,000 m of lower Paleozoic rocks are present. Although unfossiliferous, the lower 600 m can be equated, at least in part, to rocks of certain Cambrian age in Jordan. Higher beds contain intervals confidently dated as Lower Ordovician, Silurian, and Lower Devonian. Lower Paleozoic rocks are chiefly coarse-grained sandstone of terrestrial origin, although marine shale occurs at several levels and the upper 300 m is mainly shale with thin beds of limestone.

Lower Paleozoic strata are succeeded in the central escarpment region by a thick sequence (about 1,000 m) of Upper Permian

and Triassic sedimentary rocks. The initial deposit, the Khuff Formation, is mostly shallow-water limestone; overlying beds are nonmarine elastics except for thick carbonate units in the middle part of the section.

Above the Triassic System is some 200 to 500 m of Lower and Middle Jurassic rocks which, near the middle of the escarpment region, are interbedded marine shale and shelf limestone. These grade to sandstone, in part continental, in the northern and southern areas of outcrop. The Middle Jurassic is overlain by a great sequence of nearly pure carbonate rocks, highly fossiliferous and accurately dated as Upper Jurassic and early Lower Cretaceous.

The Jurassic System is spectacularly displayed in central Arabia where it forms the backbone of the escarpment region—the Tuwayq Mountains. Carbonate sedimentation was interrupted several times in the closing stages of the Jurassic by the onset of evaporite conditions which gave rise to cyclic deposits of anhydrite and calcarenite. The resulting sequence—the Arab Formation—is of prime importance for its porous carbonate members contain billions of barrels of proved oil reserves.

The carbonate sequence is succeeded by a thick body of late Lower and Middle Cretaceous sandstone. (The Middle Cretaceous Series and Epoch, as defined by European geologists, are used in this report.) Late Lower Cretaceous rocks are non-marine and appear only in the middle and southern parts of the escarpment region. Middle Cretaceous rocks, nonmarine in the south, become progressively more marine in the north where they follow a transgressive path northwest across older beds as far as Jordan.

Upper Cretaceous and Eocene rocks, almost exclusively in limestone and dolomite facies, are extensively exposed along the eastern edge of the escarpment belt and continue northwest into Iraq. The sequence, with an average thickness of about 500 m, includes rocks of Upper Cretaceous, Paleocene, lower Eocene, and middle Eocene ages.

The stratigraphic sequence above the Eocene consists of 200 to 600 m of Miocene and Pliocene rocks, mostly of nonmarine origin. These deposits—a heterogeneous assemblage of marly sandstone, sandy marl, and sandy limestone—blanket the Rub' al Khali and northeastern Arabia.

Above the Miocene and Pliocene rocks are unconsolidated Quaternary deposits which comprise great sand deserts and widespread gravel sheets. Sand of the Rub' al Khali Desert alone covers about 600,000 sq km (230,000 sq mi) or most of southern Arabia.

Two major structural provinces are recognized within the Arabian Peninsula and adjacent areas. One is the comparatively stable interior region whose rigidity is controlled by the Precambrian basement. The other is the great mobile belt of Taurus, Zagros, and Oman Mountains, bordering the stable

¹Of the Arabian-American Oil Co.

region on the north and east. Saudi Arabia falls entirely within the stable region.

The interior stable region contains the Arabian shield as well as the Arabian Shelf—an extension of the basement thinly veneered with little-disturbed sedimentary rocks. Widespread structural events, presumably related to epirogenic movement within the basement, have divided the Arabian Shelf into several distinct and significant structural elements—the Interior Homocline, the Interior Platform, and several basinal areas.

Bordering the shield is a great belt of sedimentary rocks whose dip basinward is so slight and uniform as to be imperceptible to the eye. This Interior Homocline has an average width of about 400 km and a persistent dip varying from slightly more than $1^{\circ}00'$ in older units to less than $0^{\circ}30'$ in the youngest. One structural feature of the homocline—the central Arabian arch—has greatly influenced the present surface distribution of sedimentary rocks in the interior escarpment region. The arch, which affects all rocks from the basement up, marks the area of maximum curvature of the homocline in central Arabia. Although the arch has a varied history, it is apparently a residual high between the periodically sinking Persian Gulf and Rub' al Khali basins rather than a true independent positive feature. Support for this concept comes from the presence of a great arc of tensional structures—the central Arabian graben and trough system—near the crest of the arch and along the hinge line between the Persian Gulf basin and the stable western block.

Bordering the homocline is the Interior Platform, a remarkably flat area of varying width in which systematic dip off the crystalline core no longer prevails. Superimposed on the platform are several major north-south anticlinal trends which include the great oil fields of Arabia.

Adjacent to the platform are several basinal areas that have from time to time received thick sedimentary deposits. Such basinal sags have developed on the shelf in the northeastern Rub' al Khali, northern Persian Gulf, Dibdibah and Sirhan-Turayf areas.

INTRODUCTION

An impressive amount of geological information on Saudi Arabia has been collected during Arabian-American Oil Co. (Aramco) operations, in the last 30 years. Most of the data are included in company reports; much of what appears in this paper has largely been anticipated in articles by Steineke and Bramkamp (1952 a, b), Thralls and Hasson (1956), Steineke and others (1958), Bramkamp and Powers (1958), and Powers (1962).

The objective of this report is twofold: (1) To bring together in a single document a comprehensive summary of what is now known of the sedimentary rocks exposed in Saudi Arabia and (2) to describe the sedimentary geology of Saudi Arabia as depicted on the recently published 1:2,000,000-scale map of the Arabian Peninsula (U.S. Geological Survey—Arabian-American Oil Co., 1963). Much of the text is devoted to a systematic account of the stratigraphic and paleontologic record in the Kingdom. Within individual stratigraphic units, local rock sequences are described in considerable detail. These local sections are related to each other and to equivalent rock se-

quences outside Saudi Arabia to depict the distribution, lateral change, age, and gaps in the stratigraphic record, somewhat tedious but necessary prerequisites to unraveling the geologic history of the subcontinent. Much less space is devoted to structure, and only the major tectonic elements of Saudi Arabia and adjacent areas are considered in any detail.

This report is fundamentally a compilation and, as such, presents the findings of the Aramco geologic group as a whole. A few of the ideas and basic data are new; most are not, although a number of the relatively broad generalizations have been reached but recently. Many of the concepts presented here originated with individuals, particularly the late Max Steineke and the late R. A. Bramkamp, former Aramco chief geologists. Still other fundamental ideas originated spontaneously with the group rather than with individuals. The writers, of course, take responsibility for the manner in which the concepts are presented and supported here.

HISTORY OF EXPLORATION IN SAUDI ARABIA

References to the geology of Saudi Arabia prior to the start of oil search in 1933 are scarce. Camel trips across the interior escarpment by Philby, during World War I and later years, provided the first concrete evidence that marine rocks are extensively exposed in central Arabia, (Philby, 1922, 1928, 1933, 1939). Collections made on these early travels indicated the presence of lower Kimmeridgian (Newton, 1921) and Callovian (Cox in Philby, 1933) carbonates. Little else specific was known of the geology of this vast region.

On May 29, 1933, the Saudi Arabian Government granted an oil concession to Standard Oil Co. of California. Less than four months after the concession agreement was signed, the first geologists, R. P. Miller and S. B. Henry, arrived at the seaport of Al Jubayl, and systematic surface mapping of the coastal area started. Soon these geologists were followed by others, including Max Steineke (Sidney Powers Memorial Medalist, 1951). By 1935, two-man reconnaissance parties had penetrated south as far as Yabrin (lat $23^{\circ}15'$ N., long $49^{\circ}00'$ E.), northwest to Hafar al Batin (lat $28^{\circ}26'$ N., long $45^{\circ}58'$ E.), and west across Ad Dahnā' to the Precambrian basement.

Structure drilling began late in 1936 in the Al Qatif-Al 'Alah area; seismograph was first used at Abu Hadriyah early in 1937. By this time the initial objective of getting a general picture of the concession had been achieved—the succession of geologic strata had largely been worked out, the broad geologic pattern of the area deciphered, the major uncon-

formities recognized, and most of the rock units named.

Dammam Dome, a salt dome, was the first prospect to be tested by deep drilling. Dammam well 1 was spudded on April 30, 1935. Results were disappointing, and the well was abandoned after reaching the Middle Cretaceous. Nine more wells were later drilled at Dammam; although some of these were promising, none proved out on sustained testing. Thus, the Middle Cretaceous zones, productive at nearby Bahrain Island, had proved a disappointment in ten wells. Dammam well 7 was the first well programmed to test deeper strata. Drilling of well 7, suspended while the Middle Cretaceous was tested, was resumed in late 1937. This well encountered first gas and then large quantities of oil in the Arab Formation (late Upper Jurassic). The first test to yield oil was made on March 4, 1938, and Dammam 7 was completed in the C Member of the Arab Formation later the same month.

Geological exploration was carried forward steadily, and by the fall of 1937 nine field parties were working in the concession. Surface mapping, seismograph studies, and structure drilling continued, and in 1939 a gravimeter-magnetometer survey was started in the coastal area. This same general level of activity continued until 1940 when work was gradually curtailed with the advent of World War II. When the war forced a general suspension of operations, Aramco geologists had mapped in detail some 50,000 square miles and had completed reconnaissance surveys over an additional 175,000 sq mi. They had penetrated into the northern portions of the Rub' al Khālī, southwest as far as Wādī ad Dawāsīr, west across the Tuwayq Mountains in several areas, and northwest to Wādī as Sirhān adjacent to the Jordan border. During this period oil was discovered at Abū Hadriyah in 1938 and Abqaiq in 1940, unsuccessful wildcats were drilled at Al 'Alāh in 1937 and Ma'qalā' in 1940, and a triangulation network was started to provide accurate control for the various surveys then under way.

Exploratory work was sharply limited during the war years, although surface mapping and structure drilling continued on a small scale until 1942. An unsuccessful wildcat well was started at Jauf (Al Ju'f) in 1943, and from late 1944 to mid-1945, two surface-mapping parties were in the field.

After the war, exploration once again increased nearly to its former level, and eight field parties of various kinds were in operation. Two of these were surface-mapping parties which, by the end of 1954, had surveyed much of the concession, in part by reconnaissance traverses but mostly in considerable detail. Only limited investigations of special outcrop problems have been carried out since that time. High-altitude photog-

raphy was of particular help in this phase. Between 1949 and 1958, 1:60,000-scale photographs of all Aramco's concession and much of the remaining parts of the Arabian Peninsula became available.

By 1959, subsurface geological exploration of one kind or another had reached even the remotest parts of the remaining concession, including the offshore area, and party strength was reduced accordingly. Full gravimeter-magnetometer coverage had been achieved in 1958. Two land seismic crews, supplemented for a short period by a marine unit, were in operation until early 1963; three land parties have been active since that time.

An especially interesting feature of the seismic program is that in 1958 Aramco embarked on a refraction survey which was to eventually result in a network blanketing the entire concession. The fortuitous arrangement of a nearly concession-wide, competent, anhydrite refractor immediately above the main producing interval in the Arab Formation made this method of structural mapping highly effective.

The relatively expensive and shallow-penetration structure drills were gradually phased out, and the last hole of this type was completed in 1961. Deep stratigraphic drilling was substituted. Wells 5,000 to 10,000 feet deep were spaced uniformly around the margin of the concession and scattered through the interior of the operating area. Information provided by these wells has proved invaluable, bearing heavily on regional correlation, presence and amount of truncation of unconformities, facies changes, and distribution of favorable reservoir rocks. In addition the deep holes provide critical velocity control for the seismic refraction network. Two such stratigraphic drills were active until mid-1963; one was still in operation in 1965.

During the early postwar period, wildcat drilling discovered oil at Qatif (Al Qatīf) in 1945, at Ain Dar ('Ayn Dār) in 1948, and at Haradh (Harād) and Fadhili (Al Fādīlī) in 1949. Aramco's first offshore discovery came in 1951 with the drilling of the Safaniya (As Saffāniyah) structure in the northwestern Persian Gulf. Further discoveries in 1951, 1952, and 1953 at 'Uthmaniyah (Al 'Uthmāniyah), Shadqum (Shadqam), and Hawiyah (Al Hawiyyah) established Ghawar (Al Ghawār) field, a single anticline—oil-filled from Haradh to Ain Dar and Fazran, a distance of nearly 250 kilometers. Other wells on untested structures and major exploratory wells in known fields followed in quick succession and resulted in commercially important finds at Khursaniyah (Al Khursāniyah) in 1956, Khurais (Khurays) in 1957, Manifa (Manīfah) in 1957-58, Abū Hadriya (Abū Hadriyah) in 1959, Fadhili in 1962, Abū Sa'fah in 1963, and Qatif in 1963.

Wildcats not finding commercial oil were drilled at Al 'Ubaylah in the central Rub' al Khālī in 1953-55 and El Haba (Al Lihābah) in 1963.

At the end of 1963, Aramco had discovered productive oil in eleven widely scattered fields and sixteen different reservoirs. Total estimated remaining proved reserves of crude oil were about 55 billion barrels at the close of 1963.

HISTORY OF ARABIAN MAP PROJECT

Aramco's exploration entered a particularly interesting phase in 1954 when the U.S. Geological Survey and Aramco began work on a series of geologic-geographic maps covering all the concession and most of the Peninsula. The cooperative effort was sponsored jointly by the Kingdom of Saudi Arabia and the U.S. Department of State. The purpose of the program was to make readily available for scientific and economic application the geologic data collected by Aramco and U.S. Geological Survey during the course of their many years' work in the Kingdom.

Saudi Arabia is one of the few countries in the world that has been completely covered by high-altitude aerial photography. Aerial mapping began in 1949, and 250,000 sq mi of eastern Arabia had been photographed by 1951. Remaining parts of the Kingdom involving some 550,000 sq mi were covered from 1954 to 1959. All photography was flown under strict photogrammetric specifications with the necessary forward and sidelay to give complete stereoscopic coverage.

While aerial mapping was in progress, Aramco was busy on an extensive survey network to provide accurate horizontal and vertical control. A third-order triangulation net and a second-order level net were extended over most of the Eastern Province and southward into the central Rub'al Khālī. Elsewhere, high-order astronomical observations using meridian transit stars, recording chronograph, and chronometer were established. Over much of the central outcrop area this work was augmented with stadia and barometer traverses; control developed over a 15-year period to accurately tie down the extensive geologic field work. All previously established control points and geologic field stations were identified on photographs. The points thus recovered provided the basic topographic and geologic control needed to map the Najd-Tuwayq area. A shoran trilateration net extending southward from the Saudi Arabia-Jordan border through northwestern Arabia and into the western Arabian Shield provided control over this area. Photography of the eastern Rub'al Khālī was also shoran controlled.

The first step in the preparation of the 1:500,000-scale maps was compilation of a topographic base. Each base was later to be overprinted with the geology. Basic control was provided over most of the area of Aramco responsibility by the slotted-template method of laydown firmly tied to horizontal control points identified on photographs. In the eastern Rub'al Khālī, control was established by computing geographic coordinates from shoran readings. Prior to transferring the data to the geographic base, topographic features were outlined on individual photographs. In marking the photographs, maximum detail was preserved to show relief, escarpments, drainage, culture, and other features. Sand-covered areas were defined, and dune crestinles were delineated. This material was then transferred by sketchmaster to the laydown base. Hachures were used to represent relief in areas of outcrop, and bodies of sand were shown by stippling to depict trends and different types of sand terrain.

Throughout the many years of exploration, an important function of the field parties was to gather place names. Aramco's Arabian Affairs Division, Government Relations Organization, played a major role in evaluation of the data collected and in the selection and proper placement of names used in the map series. Saudi Arabians from all parts of the Kingdom were consulted by Aramco's Arabists to assure accuracy of transliteration and to evaluate old names and obtain new ones. All names were reviewed by the Board on Geographic Names in Washington, D.C. for conformance with the BGN/PCGN system of transliteration.

The geologic map series was compiled in almost the same manner as the geographic series. The great amount of field data collected over the years had to be compiled, and in the process plane-table traverses, car traverses, and geologic stations had to be identified on photographs and adjusted to the new map base. Elevations were reviewed, adjusted, and tied to later level lines. Stratigraphic contacts were identified and traced on photographs across areas not covered by ground traverses.

After completion of the 1:500,000-scale geologic sheets and the revised 1:2,000,000-scale geographic map, Aramco personnel began work on their portion of a 1:2,000,000-scale geologic map of the Arabian Peninsula. Contributor geology was generalized on the geographic base in close collaboration with the authors. In addition, hand-colored proof was returned to each contributor for review and comments before publication. Concurrently, members of the U.S. Geological Survey were moving ahead with compilation of the geology of the western Arabian Shield.

ACKNOWLEDGMENTS

As stated before, this paper basically represents a compilation of many geologists' work over a period of 30 years. During that time 77 individuals studied the Arabian outcrop sequence and were involved in the collection and processing of the data and the formulation of the ideas expressed here. Each of these Aramco geologists is cited individually. Other members of Aramco's geologic staff made significant contribution in the form of paleontologic determinations, photogeologic mapping, and other work. It is not possible to acknowledge separately each contribution but it should be noted that the following Aramco specialists have added to our knowledge of Arabian geology: P. R. Aswerus, G. R. Ball, T. C. Barger, H. S. Bennett, Jr., E. L. Berg, S. Bevan, B. Beverly, Jr., G. W. Blakslee, H. W. Blodgett, L. E. Bogle, F. Bourgeois, S. D. Bowers, R. A. Bramkamp, A. B. Brown, C. W. Brown, H. L. Burchfiel, R. B. Carr, A. E. Clements, M. C. Coffield, J. S. Cruise, W. Dell'Oro, W. C. Dimmock, J. J. Donohue, D. B. Eicher, C. R. Farquhar, O. B. Fenner, F. J. Frankovich, W. M. Furnish, R. D. Gierhart, T. F. Harriss, D. O. Heimer, S. B. Henry, B. B. Hill, W. H. Hoag, Jr., D. A. Holm, R. W. Holt, J. W. Hoover, B. R. Hudson, R. C. Kerr, H. A. Kimball, T. W. Koch, R. P. Kopp, N. M. Layne, Jr., R. L. Maby, Jr., R. D. MacDougall, H. L. McAlister, H. A. McClure, L. B. Milam, R. P. Miller, C. S. Morse, R. L. Myers, O. W. Nine, J. W. Northrup, L. D. Owens, K. R. Parsons, A. F. Pocock, R. W. Powers, L. F. Ramirez, C. D. Redmond, D. O. Reese, W. H. Reiss, S. J. Roach, C. W. Rock, N. J. Sander, R. M. Sanford, H. W. Schneider, J. R. Schultz, J. B. Sheehan, A. M. Short, W. T. Short, Max Steineke, J. W. Thomas, F. R. Waldron, J. C. Wells, A. A. Weymouth, J. S. Williams, and M. P. Yackel.

Two of the Aramco geologists—Max Steineke and R. A. Bramkamp—should be singled out for special mention. Both were pioneers in the study of the geology of Saudi Arabia. Steineke arrived in the field September 20, 1934, almost one year after oil exploration had commenced. Bramkamp arrived in mid-September of 1936. Most of the work on which this report is based was either done by them personally or under their guidance, for Steineke and Bramkamp were Aramco's chief geologists respectively from 1936 to 1947 and 1947 to 1958. Both men were true scientists and outstanding geologists, and it was during their tenure that the framework of the stratigraphy and structural geology of Arabia evolved in much its present form. A large amount of new work, much of it detailed, has done little to modify their basic

concepts; indeed, such data have usually served to strengthen their predictions.

This acknowledgment would be incomplete without mention of S. D. Bowers who read much of the manuscript and offered many useful suggestions and criticisms. Thanks are also due James P. Mandaville, Jr., Geographical Analyst, Aramco's Arabian Affairs Division, for his painstaking research and reading and correcting of all Arabic place names appearing in this paper. The manuscript was typed by Mary E. Archer who, in addition, thoroughly edited the manuscript for place names and technical errors. For all her help the writers are most grateful. The manuscript is published by permission of Aramco.

STRATIGRAPHY

OUTLINE OF MAJOR STRATIGRAPHIC DIVISIONS
GENERAL FEATURES

The foundation for sedimentary deposition in Saudi Arabia can readily be generalized into two positive structural elements—on the west, the western Arabian Shield, a vast dominantly Precambrian complex of igneous and metamorphic rocks; on the south, the Arabian part of a crystalline massif extending northeast from the horn of Africa.

The western Arabian Shield must be regarded as a continuation of the adjacent African shield and is now separated from it by the Red Sea rift. The time of initial separation is still controversial; however, the Red Sea appears to be primarily a late Tertiary feature. Western shield rocks can be clearly dated as Precambrian by their unconformable position beneath unaltered sediments which in Jordan have furnished Cambrian fossils. The oldest identifiable fossils so far discovered in Saudi Arabia proper are Early Ordovician, but a substantial sequence of rocks correlative with the Cambrian units in Jordan intervene between these and the basement. Age of the southern Arabian complex in Yemen, the Aden Protectorates, and Dhufar also appears to be Precambrian for the most part, although the presence of some early Paleozoic elements has been determined by radioactive dating.

Since Precambrian time the massifs have been amazingly stable, subject only to gentle, epeirogenic movement. On these rigid peneplaned land masses was deposited a thick sequence of continental and shallow-water shelf sediments that dip gently into the Mediterranean, Persian Gulf, and Rub' al Khāl basins. The opposite flank of the Mediterranean-Persian Gulf geosyncline is formed by the Russian Platform far to the northeast. Presumably the Rub' al Khāl basin is a reflection of the broad northeast-plunging syncline connecting the western Arabian and southern Arabian Shields.

Field work in Saudi Arabia in connection with oil search has now been in progress for 30 years. During this time, Aramco geologists have identified, measured, and mapped in considerable detail an aggregate total of nearly 5,500 meters (18,000 ft) of sedimentary rocks ranging in age from presumed Cambrian to Pliocene(?) (table 1, pl. 1). The main rock units have been blocked out, and their limits have been tested widely enough to assume that they will stand in essentially their present form. As always, much work remains to be done—particularly so far as paleogeography, regional lithofacies, and more precise dating of some parts of the section are concerned. It is expected, however, that additional work will affect only the detail and that the major framework as now defined will survive.

Paleozoic, Mesozoic, and lower Tertiary sedimentary rocks are magnificently exposed in central Arabia. Here, rocks crop out in a great curved belt flanking the eastern margin of the shield. Beds certainly reflecting buried basement configuration dip gently and uniformly northeast, east, and southeast. Rate of dip changes progressively from slightly more than $1^{\circ}00'$ in older units to less than $0^{\circ}30'$ in the Upper Cretaceous and Eocene. Low dip of such remarkable constancy gives rise to one of the fundamental structural provinces of the Arabian Peninsula—a wide Interior Homocline bordering the Arabian Shield (pl. 2). Dominating the exposed part of the homocline is a series of essentially parallel, west-facing, strike escarpments, each supported by a resistant limestone cap. Sandstone and shale, less resistant at least so far as arid weathering is concerned, floor intervening valleys and plains. The west-facing scarps offer fine opportunity for studying the sequence in that exposures are unusually good and some rock units can be traced without significant interruption over a distance of 500 to nearly 1,000 km. As the softer formations between cuestas are very often only partially masked by late gravels and sands, even these units are fairly well known.

East of the homocline is a broad expanse of relatively low-relief terrain in which older rocks are buried by Tertiary and other late deposits. Paleozoic and Mesozoic strata do not reappear at the surface until the Oman Mountains in the easternmost part of the peninsula and Iran on the far side of the Persian Gulf are reached. In this broad area, which includes the Rub' al Khali desert and much of northeastern Arabia, specific information on pre-Tertiary rocks is available only from a few widely scattered stratigraphic holes and fields where oil wells have been concentrated—sparse control when the size of the area involved is considered.

In extreme northwestern Saudi Arabia, largely lower Paleozoic sedimentary rocks are exposed. Gentle dip

of Paleozoic units off the Arabian Shield to the east, northeast, and north outlines the continuation of the Interior Homocline west of An Nafud. A basinal area bordering the homocline on the north is characterized by a thickened Upper Cretaceous to Tertiary sedimentary section. In addition, Tertiary to Recent volcanic rocks cover substantial parts of the area.

The sedimentary section exposed above the Precambrian in Saudi Arabia falls naturally into eight major divisions. Dominated by a characteristic lithology and separated by significant breaks in the geologic record, the divisions are:

1. Lower Paleozoic clastic rocks—Cambrian(?) through Lower Devonian; dominantly coarse clastic rocks but with some thin, carbonate beds in uppermost part.
2. Permian and Triassic clastic rocks—Upper Permian through Upper Triassic; alternating nonmarine-marine units, dominantly clastic but with thick calcareous sections at base and in middle.
3. Lower and Middle Jurassic clastic and carbonate rocks—Toarcian to Callovian(?); in central Arabia marine shale interbedded with carbonate grades to sandstone in northern and southern areas of outcrop.
4. Upper Jurassic and early Lower Cretaceous carbonate rocks—Callovian through Valanginian; mostly carbonate but with alternating evaporite-normal marine cyclic deposits near end of Jurassic.
5. Late Lower Cretaceous clastic rocks—Hauterivian through Aptian; dominantly coarse clastic rocks with thin basal carbonate unit.
6. Middle Cretaceous clastic rocks—Cenomanian to Turonian(?); dominantly coarse clastic rocks.
7. Upper Cretaceous to Eocene carbonate rocks—Campanian through Lutetian; carbonate units but in subsurface lower Eocene includes evaporite section.
8. Miocene and Pliocene clastic rocks—dominantly sandy limestone and sandstone.

LOWER PALEOZOIC CLASTIC ROCKS OCCURRENCE AND CHARACTER

In northwestern Saudi Arabia at least 1,900 m of Lower Devonian and older Paleozoic rocks are exposed. Exposures extend southeast from the Jordan border, form a gently curving arc parallel to the northern margin of the shield, and disappear eastward under the blanket sands of An Nafud. Shallow dips progressively shift from northeast to north and northwest to outline a separate embayment of Paleozoic platform sedimentary rocks west of the Ha'il arch (long $41^{\circ}30'$ E.). Equivalent sedimentary rocks again crop out south of An Nafud. Here they are gradually overlapped by Permian beds and wedge out completely near lat

TABLE 1—Saudi Arabian outcrop sequence

Age		Formation	Generalized lithologic description	Thickness (Type or reference section)	Major stratigraphic divisions	
CENOZOIC	QUATERNARY AND TERTIARY		Surficial deposits	Gravel, sand, and silt		
	TERTIARY	Miocene and Pliocene	Kharj	Limestone, lacustrine limestone, gypsum, and gravel	28 m	
			Hofuf	Sandy marl and sandy limestone, subordinate calcareous sandstone. Local gravel beds in lower part	95 m	
			Dam	Marl and shale, subordinate sandstone, chalky limestone, and coquina	91 m	
		Eocene	Hadruk	Calcareous, silty sandstone, sandy limestone, local chert	84 m	
			Dammam	Limestone, dolomite, marl, and shale	33 m	
			Rus	Marl, chalky limestone, and gypsum, common chert and nodular quartz in lower part. Dominantly anhydrite in subsurface	56 m	
	Paleocene	Thapsalian Montian(?)	Umm er Radhuma	Limestone, dolomitic limestone, and dolomite	243 m	
		Possible discontinuity				
	CRETACEOUS	Maastrichtian	Aruma	Limestone; subordinate dolomite and shale. Lower part grades to sandstone in northwestern and southern areas of outcrop	142 m	
		Campanian				
		Turonian(?)	Wazu (Sakaka Sandstone of northwest Arabia)	Sandstone, subordinate shale, rare dolomite lenses	42 m	
		Cenomanian				
		Aptian	Biya	Sandstone; subordinate shale	425 m	
		Barremian				
		Hauterivian	Burwal	Biogenic calcarenite and calcarenitic limestone in interbedded with fine sandstone in upper part	18 m	
		Valanginian	Yamama	Biogenic pellet calcarenite, subordinate ephanitic limestone and biogenic calcarenitic limestone	46 m	
		Berriasian	Sulay	Chalky aphanitic limestone, rare biogenic calcarenite and calcarenite limestone	170 m	
			Hith	Anhydrite	90 m	
		MESOZOIC	Tithonian	Arab	Calcareous, calcarenitic and ephanitic limestone, dolomite and some anhydrite. Solution-collapse carbonate breccia on outcrop due to loss of interbedded anhydrite	124 m
	JURASSIC		Kimmeridgian	Jubaila	Aphanitic limestone and dolomite; subordinate calcarenite and calcarenitic limestone. Lower part sandstone between 20° N and 22° N	±118 m
				Hanifa	Aphanitic limestone, calcarenitic limestone, and calcarenite	113 m
			Oxfordian	Tuwaiq Mountain	Aphanitic limestone; subordinate calcarenitic limestone and calcarenite. Abundant corals and stromatolites in upper part	203 m
Callovian						
Callovian(?)	Dhurma		Aphanitic limestone and shale; subordinate calcarenite. Dominantly sandstone south of 22° N and north of 26° N	375 m		
Bathonian						
Bayesian						
Toarcian	Marrat		Shale and aphanitic limestone, subordinate sandstone	103 m		
TRIASSIC	Upper		Minjur	Sandstone, some shale	315 m	
	Middle	Jilh	Sandstone, ephanitic limestone, and shale; subordinate gypsum	±326 m		
	Lower	Sudair	Red and green shale	116 m		
PALEOZOIC	PERMIAN	Upper	Khuff	Limestone and shale; dominantly sandstone south of 21° N	171 m	
		Lower	Wajid	Sandstone, gravel, and basement erratics (Recognized only in southwestern Saudi Arabia and northern Yemen)	950 m calculated	
	DEVONIAN	Precambrian basement complex				
		Lower	Jaul	Limestone, shale, and sandstone	299 m	
			Tabuk	Sandstone and shale	1,072 m	
	ORDOVICIAN	Saq	Umm Sahn Ram Qawra Dq	Sandstone	+ 600 m	

Precambrian basement complex

Compiled by R. W. Powers and
L. F. Ramirez, June 3, 1963

24°20' N. Intervals within this sequence have been dated by graptolites and brachiopods as Lower Ordovician (Arenig), Silurian, and Lower Devonian. Cambrian fossils have not been found, although recent photo-geological work shows the lower part of the section to be equivalent to Jordanian units of certain Cambrian age. Major internal unconformities have not been detected, but their absence cannot be assumed on the basis of sparse field work so far done.

Silicate clastic rocks dominate the entire lower Paleozoic succession. The lower one-third is almost exclusively white, buff, and red, medium- to coarse-grained, crossbedded sandstone. A thick section of graptolite-bearing shale alternating with light-colored, micaceous, commonly crossbedded sandstone follows. Capping the sequence is nearly 300 m of shale with subordinate stringers of sandstone and carbonate.

In southwestern Arabia a thick sandstone intervenes between basement and Upper Permian carbonate rocks. Unfortunately, this unit has proved barren, and complete or even partial equivalency to Paleozoic clastic rocks in the northwest has not been established. Flora from adjacent bore holes does suggest, however, that Lower Permian as well as Carboniferous and even Devonian may be represented. The possible presence of still older Paleozoic rocks is not disproved. Exposed in northern Yemen as outliers on the eroded Precambrian surface, the massive sandstone, in Saudi Arabia, forms a wedge of nearly continuous outcrop as far north as Wādī ad Dawāsīr (lat 20°30' N.). At this point the sandstone pinches out between basement and overlapping Permian limestone. Calculated to be more than 900 m thick, the postbasement wedge is mainly coarse-grained sandstone including common gravel beds and some zones of basement erratics.

RELATIONSHIP TO ADJACENT UNITS

Precambrian elements of the Arabian Shield were buckled, firmly stabilized, and had undergone at least one and possibly several periods of erosion and penetration before the first Paleozoic sediments were deposited. Marked nonconformity is everywhere evident between basement and overlying sediments.

The lower Paleozoic sequence is terminated at the top by definite unconformity. South from An Nafūd, pre-Permian erosion progressively eliminates Devonian, Silurian, Ordovician, and Cambrian(?) beds, eventually bringing Permian rocks into contact with basement near the latitude of Ad Dawādīmī (lat 24°29' N.). From here the erosion surface can be traced south across the basement arch of central Arabia and again effects the southern wedge of Paleozoic clastic rocks.

Beneath An Nafūd other unconformities come in. First, pre-Middle Cretaceous erosion eliminated the

Permian, probably north of Hā'il, and cut into Lower Devonian. West of Al Jawf, the Middle Cretaceous is, in turn, truncated by pre-Upper Cretaceous erosion that eventually cut deep enough to completely remove the Lower Devonian.

Time represented between basement stabilization and the beginning of presumed Cambrian sedimentation is unknown. However, fair dating of units bracketing the upper unconformity shows approximately Middle Devonian through middle Permian time unrecorded in outcrop. Until recently, rocks of these ages had not knowingly been found anywhere in Saudi Arabia. Now, however, spore and pollen analyses show that one well in northern Arabia (near lat 29°50' N., long 41°50' E.) penetrated shale of Mississippian and Pennsylvanian age (Viséan to Westphalian). Other wells contain Upper Devonian, Carboniferous, and Lower and middle Permian rocks, thus filling out the Paleozoic record.

PERMIAN AND TRIASSIC CLASTIC ROCKS OCCURRENCE AND CHARACTER

Nearly 1,000 m of Permian and Triassic sedimentary rocks are exposed in a wide belt that curves around the eastern margin of the Arabian Shield. The sequence falls naturally into four subequal units which apparently represent alternating marine and nonmarine deposition. At the base limestone and dolomite alternate with red and green gypsiferous shale. Next above is unfossiliferous brick-red and green shale, presumably nonmarine. A thick section of limestone interbedded with light-colored sand and some gypsiferous shale follows. At the top are highly colored clastic beds containing petrified wood as the only recognizable organic constituents, characteristics that suggest the unit is mainly continental. As a whole, the Permian and Triassic appear to be mixed marine and continental clastics, the latter predominating.

Only the sketchiest time framework has been supplied to the outcrop by marine fossils. The lower carbonate unit contains molluscs which have been assigned a probable Late Permian age. Higher carbonate stringers contain fragments of ammonites considered to be Middle Triassic. Fortunately, nearby bore holes have yielded rich suites of diagnostic spore and pollen from equivalent beds. On the basis of these, it is safe to say that the outcrop contains an almost complete Upper Permian through Upper Triassic (Keuper) sequence.

RELATIONSHIP TO ADJACENT UNITS

Regionally important unconformities above and below set the Permian and Triassic strata off from bracketing units. The lower contact is marked by Upper Permian beds discordantly on rocks as widely varied in age as: Precambrian (across the central Arabian arch); Cambrian through Early Devonian (north of the arch);

and middle Permian and older (in the south). At the top, Upper Triassic is overlain by beds of Toarcian age (upper Liassic), and lower Liassic is missing over the length of outcrop. In the extreme southern part of the outcrop, upper Liassic rocks are overlapped and Middle Jurassic rests directly on Triassic.

LOWER AND MIDDLE JURASSIC CLASTIC AND CARBONATE ROCKS

OCCURRENCE AND CHARACTER

The Lower and Middle Jurassic are typically represented in central Arabia by about 500 m of shallow-water shale and carbonate. In the Riyadh-Durmá area, a thin unfossiliferous basal sandstone is followed by alternating limestone and shale—all highly fossiliferous. The lowermost carbonate bears Toarcian ammonites (uppermost Lower Jurassic) and above it, definite Bajocian and Bathonian and possible Callovian beds have been identified.

Thin members of clean, current-washed carbonate occur at various levels, often as units of high lateral persistence that are useful in setting up a framework of correlation. Lithologic changes to the south along outcrop consist primarily of gradual replacement of shale and carbonate by sandstone. The transition first takes place in the lower beds just south of lat 24° N. and progressively affects higher units so that at lat 21° N. sandstone, apparently continental, makes up the entire sequence. Hints of similar replacement can be seen to the north before interbedded sandstone and shale disappear beneath Recent cover. Although the trend toward a continental environment in this direction is obvious, it is likely that a considerable part of the unit is marine where last seen in the vicinity of Az Zilfi (lat 26°18' N.), and the actual strand line must have been even further north.

RELATIONSHIP TO ADJACENT UNITS

Beds of definite Toarcian age rest disconformably on Upper Triassic nonmarine sandstone throughout the length of outcrop. Although unconformity at this level cannot be proved by surface relationships, bore holes show extensive truncation immediately downdip and, in some places, the entire Upper Triassic is missing only a short distance basinward. South of lat 22° N. the Toarcian itself pinches out in response to progressive Middle Jurassic overlap.

The transition from Middle to Upper Jurassic, long considered to be unconformable, now is thought to take place without interruption or at the most involves only slight disconformity. Misleading was the fact that basal Upper Jurassic rocks do indeed rest with definite discordance on older units around the southern margin of the Rub' al Khali basin. Now, however,

good faunal control shows that uppermost Middle Jurassic beds are laterally persistent and are without evidence of truncation. Rather than elimination at the top by erosion, it seems more likely that the Middle Jurassic pinches out to the south by progressive onlap and loss of successively younger beds at the base. Eventually, elimination is effected by complete Upper Jurassic marine overlap.

UPPER JURASSIC AND EARLY LOWER CRETACEOUS CARBONATE ROCKS

OCCURRENCE AND CHARACTER

Upper Jurassic and early Lower Cretaceous rocks, almost entirely in shallow-water limestone facies, are spectacularly exposed in central Arabia where they stand up as a series of scarps subparallel to the eastern edge of the shield. More than 850 m of section has been measured near the latitude of Riyadh. Calcareous limestone (lime sand admixed with lime-mud matrix) predominates, although thick, often laterally persistent beds of calcarenite (clean-washed lime sand and gravel) are common at many levels. Lime sands are of various origins, but skeletal debris and aggregate pellets are most common.

The basal 200 m of Upper Jurassic section, composed of abundantly coralliferous and stromatopora-like lithographic limestone, is a massive cliff former. This unit stands up in sharp relief for more than 1,000 km to form the dominant scarp of Jabal Tuwayq, one of the major topographic features of the Arabian Peninsula. Exposed at the base of the cliff-forming unit is a zone rich in fossils considered to be middle Callovian. Strata representing remaining Upper Jurassic stages and the early Lower Cretaceous through Valanginian are deposited above without apparent interruption. The only significant change in depositional environment throughout is reflected by the exposure of massive Kimmeridgian Tithonian anhydrite in a solution sink, Dahl Hit (lat 24°39'18" N.; long 47°00'06" E.). Laterally, little is known of the true evaporite rock sequence owing to extensive removal by solution. Most of the area in which these beds would be expected to crop out is a nearly hopeless jumble of low hills representing complexly settled rocks. The collapse breccia can be traced from lat 20°45' N. to nearly lat 26° N., a distance of about 550 km. Only in the southern part of the solution-collapse zone is anhydrite present and then only in small amount. Equivalent rocks are extensively known in the subsurface where they comprise the Hith-Arab evaporite-carbonate complex.

Some lithologic differentiation is apparent in the southern part of the lower Kimmeridgian outcrop, including the appearance of a large marine sandstone

lens in the middle part of the sequence. The sand grades to limestone north of lat 22° N. and south of lat 20° N. Limited exposures in a downdip direction, that is, to the southeast, also show sandstone giving way to carbonate. In this same general area, much of the lower Kimmeridgian above the sandstone is replaced by thickly bedded dolomite. Below the sandstone Upper Jurassic carbonates show a marked buildup of clean, current-washed, shelf calcarenite. Progressive increase in calcarenite continues to the south until, between lat 18° N. and 19° N., Callovian through lower Kimmeridgian rocks are dominantly lime sand and lime gravel; presumably all mud-size particles were removed from the scene by turbulent water.

RELATIONSHIP TO ADJACENT UNITS

The contact between Upper Jurassic and older beds, apparently conformable north of about lat 19° N., becomes unconformable to the south. In this direction, Callovian limestone first laps over Lower Triassic and then successively transgresses older Paleozoic units.

The contact between the Upper Jurassic-early Lower Cretaceous carbonate succession and overlying strata involves two unconformities. Maximum section is preserved near lat 24° N. South of this parallel, pre-Hauterivian erosion uniformly cuts successively older beds until, at the southern limit of exposure near lat 18° N., lower Kimmeridgian is affected. North of lat 24° N., only a limited amount of section was removed by this unconformity before pre-Cenomanian truncation took over and rapidly eliminated remaining Lower Cretaceous to Upper Jurassic beds. The last vestige of the Tuwayq escarpment (Callovian limestone) passes under Cenomanian sandstone near lat 28° N.

LATE LOWER CRETACEOUS CLASTIC ROCKS OCCURRENCE AND CHARACTER

Except for a thin, albeit persistent, basal limestone, late Lower Cretaceous rocks in central Arabia are mainly continental sandstone. The basal carbonate unit with a measured thickness nowhere greater than 20 m, crops out as a discontinuous scarp from lat 25°30' N. nearly to the southern limit of exposure (lat 20°35' N.); clastics overlying the basal unit form a broad, flat, alluvium (gravel)-covered plain. The surface of the plain is commonly broken by hills of coarsely crossbedded sandstone elevated slightly above the alluvium floor. The belt of sandstone, a feather-edge near lat 26° N., rapidly widens to the south and then maintains a uniform width from lat 24° N. to 20°30' N., where it passes under Neogene and Recent cover. Further south, it appears again in windows at Al Jaladah and Ash Sharawrah. Incomplete exposure prohibited accurate measurement of a full section,

although compositing of several sections indicates maximum sandstone thickness to be about 700 m.

Recently an intense search and sampling of the basal carbonate unit resulted in a fine collection of rock samples, larger fossils, and foraminifera. The characteristic lithology is calcarenite and calcarenitic limestone, the sand- and gravel-size grains mostly being molluscan debris. Fine-grained sandstone is interbedded with carbonate in the upper part, and the unit shows gradational contact with the overlying continental series.

Although the megafossils have not yet been studied, relationships established by means of Foraminifera indicate that the limestone is probably Hauterivian. It is undated on outcrop, but comparison with equivalent subsurface strata shows the sandstone to be mostly if not entirely Barremian and Aptian (fig. 1).

RELATIONSHIP TO ADJACENT UNITS

Both the upper and lower surfaces of late Lower Cretaceous strata are demonstrable unconformities. Pre-Hauterivian erosion removed a small section in the north but southward cut progressively deeper until lower Kimmeridgian was involved. The upper sandstone limit was effected by pre-Cenomanian truncation. Accordingly, Albian strata are apparently not present on outcrop (as they are a short distance downdip), and between lat 24° N. and 26° N. the entire Hauterivian to Aptian section is cut out.

MIDDLE CRETACEOUS CLASTIC ROCKS OCCURRENCE AND CHARACTER

The Middle Cretaceous Series and Epoch, as defined by European geologists, are used in this report. In central Arabia the Middle Cretaceous is represented by a thin but highly persistent unit, mainly sandstone. Shale is commonly interbedded, and thin dolomite and limestone layers are present locally. Most of the sandstone is brown, and crossbedded; interbedded shale and siltstone is varicolored—red, purple, and green being most common.

The sandstone forms a narrow curved band exposed with few breaks from Wādī ad Dawāsīr north to the eastern edge of An Nafūd, a distance of nearly 1,100 km. Large patches of undifferentiated Middle and Lower Cretaceous clastic rocks have been mapped in the southwestern Rub' al Khālī at Al Jaladah and Ash Sharawrah. These exposures are the southernmost in Saudi Arabia proper. In the north, bore holes show that the sandstone continues under An Nafūd and again crops out around Sakākah. Relatively small outliers also occur southwest of Sakākah. Until recently, age of the clastic section exposed in the northwest was the subject of considerable controversy.



Now, however, lateral relationships established by wells show the sequence to be, with little doubt, equivalent to Middle Cretaceous rocks of Najd.

Thickness of the Middle Cretaceous rocks south of lat 26° N. is remarkably uniform averaging about 40 m. The unit thickens gradually to the northwest, and at Sakākah incomplete measurement suggests as much as 250 to 300 m of section.

So far as age of the sandstone-shale sequence is concerned, few fossils have been found on outcrop and these only in central Najd where thin limestone lenses occur. Here, rare ammonites have been dated as Cenomanian. Downdip in well sections, where more faunal control is available, equivalent beds are mainly Cenomanian. A thin scum of Turonian may reach the surface as well, although proof of this possibility is lacking.

RELATIONSHIP TO ADJACENT UNITS

Middle Cretaceous relationship to adjacent units, so far as outcrop is concerned, is fairly well understood; downdip the situation is less clear. The lower contact on outcrop is one of marked unconformity. South of about lat 25° N. Cenomanian sandstone rests on what is believed to be Aptian sand. North of this latitude, rapid truncation—at least in Saudi Arabia where regional unconformities commonly eliminate beds at the rate of less than 1 m per km—superimposes Middle Cretaceous on all older units down to and including Lower Devonian. At the top, Cenomanian or Turonian(?) is apparently in disconformable contact over most of the length of outcrop with Campanian(?) limestone.

Relationship to the subsurface sequence is still incompletely understood. There is considerable evidence that surface type sections of Middle and Lower Cretaceous sandstone formations do not properly match subsurface units bearing the same names (fig. 1). Difficulty of detecting unconformities and lack of fossils within the sandstone sequence play a major role in the uncertainty and inability to resolve the problem. Basically, the difficulty revolves around the "pre-Cenomanian" unconformity, so evident on Arabian outcrop, and its accurate identification in coastal wells. So far this unconformity has not been pinpointed in the subsurface, although it certainly falls much higher in the section than the upper surface of Aptian carbonate rocks with which it was previously equated. As is so often the case, recognition of a problem is one thing; its solution is another. The unconformity separating Middle and Lower Cretaceous (each a single formation) on outcrop cannot be identified in the subsurface. By the same token, the boundary as now designated between subsurface formations cannot be located in terms of the surface sequence.

UPPER CRETACEOUS TO EOCENE CARBONATE ROCKS OCCURRENCE AND CHARACTER

Upper Cretaceous to Eocene rocks are widely exposed in Saudi Arabia. In the south where its width is relatively constant, the belt of outcrop follows the trend of older units. North of lat 24° N. it almost exactly parallels the Middle Cretaceous transgressive sandstone which cuts diagonally across the strike of older units. The shift in strike is accompanied by a gradual widening of the outcrop belt and introduction of progressively younger beds at the top. For example, south of Wādī as Sahbā', Campanian(?) to Thanetian rocks are exposed across a width of 85 km. A short distance north, width of outcrop has expanded to 110 km as Ypresian and Lutetian rocks are introduced. Still further north, progressive reduction in rate of dip is reflected in continued widening of outcrop until, at Sakākah, Upper Cretaceous rocks alone are exposed across 160 km, and younger units lap over into Iraq.

Although the Cretaceous rocks are not exposed east of the main outcrop belt, the Paleocene and (or) Eocene rocks surface again near Abqaiq, at Dammam Dome, south of Qatar, and in the southeastern Rub' al Khālf. Upper Cretaceous to Eocene rocks exposed in Saudi Arabia are, for the most part, limestone and dolomite with a few very thin interbeds of marl and shale. Several of these clay-bearing units show remarkable lateral persistence both on outcrop and in the subsurface, and a few have been traced without appreciable change over northeastern Arabia and large parts of the Rub' al Khālf.

South from lat 24° N., the Upper Cretaceous section is progressively replaced from the bottom up by sandstone; complete replacement is effected just north of lat 22° N. A similar relationship exists in the extreme northwest near Sakākah where sandstone appears at the base.

RELATIONSHIP TO ADJACENT UNITS

The Upper Cretaceous to Eocene carbonate succession is separated from beds above and below by hiatus. At the base, Campanian(?) is in disconformable contact with Cenomanian and Turonian(?) clastics throughout almost the entire length of outcrop. Near Sakākah, the unconformity becomes angular; Cenomanian beds are eliminated near long 39° E., and to the west Upper Cretaceous beds rest on Lower Devonian.

Although lower Upper Cretaceous stages (Coniacian and Santonian) are not present on outcrop, they are extensive in the coastal area. Even here, however, pre-Upper Cretaceous unconformity manifests itself, primarily by truncation of beds on the crests of individual folds. While strong angular discordance is present on some structures, others show no sign of a

break at this level. It is likely that no important time gap is involved in off-structure areas, and the unconformity fades to a time line possibly falling near or on the Turonian-Coniacian boundary.

The upper limit of the Upper Cretaceous through Eocene sequence involves widespread and persistent unconformity. On outcrop and in wells drilled basinward, Miocene and Pliocene sand and sandy limestone rest on lower middle Eocene or older rocks. Extensive drilling throughout Saudi Arabia has failed to detect upper Eocene or Oligocene strata except possibly in the Sirhān-Turayf basin near Jordan.

MIocene AND PLIOCENE CLASTIC ROCKS OCCURRENCE AND CHARACTER

In northeastern Arabia, the stratigraphic sequence above the Eocene consists of a relatively thin succession (200-300 m) of Miocene and Pliocene rocks, mostly of nonmarine origin. These deposits—a heterogeneous assemblage of sandy limestone, calcareous sandstone, sandy clay, and sandstone—blanket the Eastern Province. Much of the section contains only sparse fresh-water fossils that are of no use in dating. In limited parts of the coastal area, however, marine molluscs and echinoids have been found through the middle part of the sequence. The fauna indicates approximate correlation with Lower Fars of Iraq-Kuwait and is presumably middle Miocene. Because of apparent continuity and stratigraphic position, the closing succession of Arabian Tertiary deposits is considered to be early Miocene to Pliocene(?).

A lithologically similar, although much thicker, Miocene and Pliocene sequence covers the Rub' al Khālī. Here, as much as 600 m of sandstone, sandy marl and sandy limestone filled and leveled the Rub' al Khālī depression. Only rare nonmarine fossils have so far been recovered from this clastic section in spite of a relatively uniform network of bore holes through the area.

RELATIONSHIP TO ADJACENT UNITS

Miocene and Pliocene rocks everywhere rest unconformably on Eocene or older beds; Oligocene deposits are unknown. Unconsolidated sand and gravel, presumably for the most part Quaternary and Recent, are erratically superimposed on the Miocene and Pliocene sequence.

PALEOGEOGRAPHY EARLY PALEOZOIC

Data on Middle East Cambrian to Devonian rocks are too incomplete to furnish any satisfactory picture of the paleogeography of those times. The problem is further complicated by the fact that occurrences of these systems are largely inadequately dated and hence equivalencies are usually uncertain.

CAMBRIAN

Rocks of proved or presumed Cambrian age occur only sparsely in areas immediately adjacent to Saudi Arabia. Cambrian strata have been described from southwestern Jordan where they are exposed in a thin belt bordering the Dead Sea rift. Much of this section is sandstone and gravel, although, opposite to the Dead Sea, it includes a thin shale-carbonate unit containing Middle Cambrian trilobites. Almost certainly, the Jordan sequence is a continuation of the chiefly continental, but also in part littoral, sandstone exposed in Saudi Arabia.

A complex of strongly folded sediments including conglomerate, sandstone, shale, tuffaceous rocks, and two well-defined carbonate units with some gypsum occurs in southwest Hāgramawt. The sequence is believed to pass westward into metamorphic rocks; eastward, the complex has been tentatively equated to a thick series of contorted clastics (including graywacke) in Dhufar and questionable Lower Cambrian clastics and dolomites in Al Huqf area of south Oman.

North of Al Huqf, in the featureless Oman Desert, are several salt domes with salt of presumed Cambrian age. These domes expose a varied assortment of rock types, including some igneous debris, which suggest correlation with the Middle and Upper Cambrian Hormuz Series of southern Iran-Persian Gulf-Trucial coast salt domes.

Cambrian rocks are widely known in southwestern Iran; many of the occurrences are associated with intrusive salt masses. The salt intrusions and related rocks of the Hormuz Complex contain fragments ranging in age from Lower Cambrian to Jurassic. Cambrian rocks have also been found in normal outcrop along the northeastern margin of the Zagros Mountains as well as within the area of salt plugs. Red shale and sandstone accompanied by subsidiary gypsum and traces of salt represent the Lower and Middle Cambrian in the northeast, and mainly salt prevails in the south. In both areas, Upper Cambrian rocks are red and green shale and sandstone with thin limestone and dolomite beds.

References to the main occurrences of Cambrian salt have been given in the preceding discussion. Roughly, the area involved is southwestern Iran, islands of the Persian Gulf north of the Trucial coast, the Trucial coast, and southern Oman. A possible outlier is found in Jabal Sanām in southern Iraq where rocks of Hormuz type are associated with a strong negative gravity anomaly. In Saudi Arabia itself, one structural feature, Dammam Dome, offers strong evidence of salt piercement origin. Other features, although salt movements may have been involved in their formation, do not

show sufficiently clear evidences of this origin to use them to outline the extent of underlying salt.

Outcrop sections in central Arabia are of little aid in outlining the original extent of the saline basin. As the dated portion of the Paleozoic is Ordovician to Lower Devonian and no slumping has been reported below this level, it is likely that saline deposits were not originally present. Thus, the limit of the area underlain by salt probably lies between Danmam Dome and the Paleozoic rocks exposed in the interior, the latter probably representing a marginal nonmarine and littoral clastic facies bordering the evaporite basin. The Lower(?) Cambrian clastic and carbonate beds (with some gypsum) exposed along the southern fringe of the Arabian Peninsula may also be marginal to and represent the opening phase of the Cambrian evaporite cycle so well recorded to the north.

ORDOVICIAN, SILURIAN, AND DEVONIAN

So far as the Ordovician in Saudi Arabia is concerned, about 400 m of clastics has been assigned to this system. Units of purple, olive-green, and gray graptolitic shale alternate with massive beds of reddish-brown to gray, in part crossbedded, and commonly micaceous sandstone. *Cruziana* tracks, none of which have been collected from the Ordovician, are found in abundance both above and below. The Arabian sequence extends without significant lithologic change into southern Jordan.

Nearly identical sandstone and shale containing *Cruziana* constitute the reported Ordovician lithologic units exposed in northern Iraq and Oman. In addition, one well in Oman near Wādī al Ghābah (lat 21°20' N., long 57°19' E.) drilled about 2,000 m of Lower Ordovician clastic rocks containing graptolites and *Cruziana*; other deep wells in Syria penetrated graptolite-bearing clastic rocks defined only as lower Paleozoic.

Described Ordovician lithologic units certainly reflect extensive shallow-water conditions in which several marine transgressions are recorded by graptolite-bearing shales, trilobites reported from Jordan, and occurrences of *Orthoceras* sp. in Saudi Arabia and Iraq. Nonfossiliferous crossbedded sandstone and other massive sands containing abundant pelecypod molds record intermittent emergence and near-shore conditions.

Silurian and Devonian rocks in Saudi Arabia are dominantly clastic and include some thin beds of limestone in the Lower Devonian. Graptolites and brachiopods attest to the marine nature of some of the section; other parts are certainly continental and transitional. With the exception of Jordan, equivalent or partially equivalent rocks are not exposed elsewhere. In most other areas immediately adjacent to Saudi Arabia such as Iraq, Yemen, the Aden Protectorates, and Oman,

the time interval is represented on outcrop by unconformity. Even in southwestern Iran, middle Paleozoic time is poorly represented by sediments, although *Monograptus*, a genus usually considered to be Silurian, has been reported from this area.

PERMIAN AND TRIASSIC

Permian and Triassic time is fairly well represented in outcrop and bore-hole sections of the Middle East. Actually, it is within these periods that clues to the outline of the major Mesozoic (Tethys) basin to the north and east of the Arabian massif begin to emerge. Roughly, the center of the Tethys trough (marked by maximum subsidence, thickest sedimentation, and deeper water deposition) forms a great arc around the Arabian Shield. It passes east through Lebanon, Syria, and Turkey; southeast across Iraq; and then, in southwestern Iran, parallels the modern Persian Gulf trend. Older Paleozoic rocks may also have been deposited, possibly in considerable thicknesses, in an ancestral basin of similar position and configuration, although evidence for this deposition is now lacking.

LATE PERMIAN

Late Permian time marks a significant change in sedimentation from dominantly clastic to mostly carbonate. During this epoch, the sea spread over much of the Arabian foreland and there deposited a sheet of shallow-water limestone that extends from northern Iraq and Turkey to Oman. In each area, the relationship to underlying units is unconformable, and the transgression initiates a period of gradual subsidence which continued with periodic interruptions into the Cenozoic.

In central and northern Najd, the Permian is dominantly limestone interbedded with shale and dolomite. The carbonate units are gradually replaced by sandstone and shale in southern Najd, most of the change taking place between lat 22° N. and 21° N. Throughout the length of outcrop a thin unit of massive brick-red and rarely green shale caps the carbonate-sandstone part of the Permian.

The subcrop of apparent-strand-line and near-strand-line clastic beds seen on outcrop between lat 18° N. and 21° N. has been traced eastward under the Rub' al Khāl by deep drilling. Roughly north of lat 21°15' N., from the Arabian Shield to Oman and southwestern Iran, Upper Permian sediments are almost exclusively carbonate; to the south clastic beds predominate. Contrary to this generalization, a well near lat 30° N., long 42° E. found the Upper Permian in full shale facies, certainly marginal to limestone deposition to the northeast.

Dolomite, replacing shallow-water clastic limestone, dominates many of the well sections of central and

coastal Arabia and the central Rub' al Khālī and also is exposed in significant amounts in sections in the Oman Mountains. Included evaporite deposits in northern Iraq and Saudi Arabia attest to the periodic existence of barred-basin conditions.

TRIASSIC

Lower and Upper Triassic rocks exposed in Saudi Arabia are respectively red and green, and commonly consist of gypsiferous shale and sandstone with varicolored shale. Fossil wood is present at several levels in the Upper Triassic, and presumably the series is mainly, if not entirely, continental. Systematic lateral variation in lithology is recognized only in the Middle Triassic. Southernmost exposures are mainly sandstone, probably in large part nonmarine. The proportion of limestone steadily increases northward (from lat 23°30' N), and carbonate rocks dominate the sequence near lat 27° N. This regional pattern is interrupted near lat 26° N. by the appearance of a major lens of bedded gypsum in the upper part. Therefore, in Arabia, rocks of continental and near-shore facies dominate the Triassic, although at least one more or less persistent marine transgression is recorded by Middle Triassic limestone.

Marginal clastic deposits also prevail in Jordan where Triassic rocks crop out near the Dead Sea, although here also thin limestone and evaporite beds also occur sporadically through the section. The Jordanian-Arabian exposures almost certainly block out in rough form the southwestern and western edges of the Triassic sea.

With recent palynological correlations, it now seems safe to extend Triassic units from outcrop into the coastal and Rub' al Khālī areas of Arabia. Similarities in lithology and stratigraphic relations offer strong support for this usage. Some reservations should be held on the age of sediments just below the pre-Jurassic unconformity because we cannot be certain that beds equivalent to the Upper Triassic on outcrop are fully represented to the east. In fact, there is some evidence that Upper Triassic rocks are entirely removed at least over the southern half of the Rub' al Khālī basin and much of the coastal province as well.

In all coastal and Rub' al Khālī wells so far drilled, the lithologic composition of the Triassic is dolomite complexly interbedded with anhydrite, limestone, shale, and some sandstone. Similar conditions must have persisted over much of the Arabian foreland for, even though details of the sequence vary, like rocks are found in the Oman Mountains, southwestern Iran, and northern Iraq. Wells drilled intermediately between the Arabian coast and the outcrop belt penetrated the same complex of rock types, although shale predominates in the south, and anhydrite, in the north.

There is little doubt that the limestone, now abundantly dolomitized, is of shallow-water origin. Original clastic textures are commonly preserved even though dolomite replacement is complete. The common occurrence of thin evaporite units throughout, as well as fetid dolomite and dark shale, attests to the fact that restricted conditions prevailed or constantly threatened. It is believed that throughout the period the basin of deposition occupied a relatively constant area with sills cutting circulation from time to time between certain parts.

EARLY AND MIDDLE JURASSIC

EARLY JURASSIC

So far as known, the passage from Triassic to Jurassic is everywhere represented either by unconformity or nonmarine sedimentation. Around the margins of the Arabian Shield, dated marine Jurassic beds are separated from undoubtedly Triassic or older units by generally unfossiliferous sandstone. These nonmarine clastics tentatively assigned to the Liassic(?) or the Liassic and Middle(?) Jurassic occur in Jordan east of the Dead Sea and on the opposite side of the rift valley, in Yemen and in the Aden Protectorates.

Although pre-Toarcian Liassic marine strata have been reported in Iraq, Kuwait, southwestern Iran, and Oman, it is with the Toarcian that widespread Jurassic transgression begins. The relative position of nonmarine Liassic(?) and marine Toarcian rocks indicates that an expanded Tethys sea covered the northern tip of Sinai, northwestern Jordan, Lebanon, much of northern Syria and eastern Iraq, and eastern Arabia (as far south as lat 22° N.) and extended eastward into Iran and across northern Oman.

Some lithologic differences between Lower and Middle Jurassic are retained over much of the basin because the Toarcian is partly sandstone and shale in Rub' al Khālī and Eastern Province wells and contains significant anhydrite in Kuwait-Iraq. Included limestones, commonly finely fragmental and oolitic, further attest to the neritic and lagoonal conditions in which Toarcian deposition took place.

MIDDLE JURASSIC

Bajocian and Bathonian time witnessed further expansion of the Tethys sea. This expansion is particularly evident in southern Arabia where the basal contact of the Middle Jurassic and succeeding Upper Jurassic carbonate units is markedly transgressive. Successively younger horizons rest on older rocks as the distance from the deeper part of the basin of deposition increases. Data from outcrops around the shield areas also show a landward shift of the mid-Jurassic shoreline relative to that defined by Toarcian sediments.

Two facies of the Middle Jurassic are recognizable in the coastal area of Saudi Arabia. From Ahl Hadriya south, aphanitic limestone, in part dark and argillaceous, dominates. Variable amounts of lime sand, usually having lime-mud matrix, are interbedded. Northward, at Jauf and Safaniya, darker, more argillaceous, presumably deeper water limestone and gray-black shale occur. In this area, few lime-sand beds are present, and these beds are admixed with dark impure mud matrix. These basinal, argillaceous limestones and gray-black shales can be traced north into northwestern Iraq and across the Persian Gulf into southwestern Iran.

Uppid, the darker sediments rapidly give way to lighter colored, commonly coarsely elastic, clean-washed shelf limestone. This neritic facies has been recognized in northwestern Jordan and central Iraq; it probably passes under the Saudi Arabia-Iraq Neutral Zone, includes Khurais, extends south into the western Rub' al Khali, and then swings east across the Oman Mountains.

A somewhat thinned group of partly impure limestones with some interbedded calcarenite represents the Middle Jurassic in a central Rub' al Khali well. Although of relatively shallow-water deposition, the facies represents somewhat deeper water deposition than that of central Najd.

As indicated earlier, Middle Jurassic units are continental clastics in southwestern Arabia, Yemen, and the Aden Protectorates. Wells along the southern margin of the Rub' al Khali show Upper Jurassic directly on Permian or older strata. Presumably, Lower and Middle Jurassic rocks in marginal facies are overlapped a short distance north.

LATE JURASSIC AND LOWER EARLY CRETACEOUS

Marine Upper Jurassic and early Lower Cretaceous rocks, dominantly in shallow-water carbonate facies, are extensively exposed in the Middle East. The carbonate succession cropping out in central Arabia is only a small part of a great belt of limestone that extends from north Africa across northern Sinai and Lebanon, covers large parts of Syria, Iraq, Iran, Oman, Yemen, and the Aden Protectorates, and continues into east Africa.

LATE JURASSIC

The episode of subsidence, expansion, and infilling of the Tethys trough that began in the Early Jurassic continued without apparent interruption into the Late Jurassic. Low-relief landmasses adjacent to the shelf contributed almost no terrestrial debris. Lime sand, derived from local sources, served as a hydraulic substitute for quartz grains, and as a result calcarenite was concentrated along the beach, piled up to form

offshore bars, and spread out in sheets over high parts of the bottom lands of the Arabian foreland. Lime mud, substituting for clay particles, came to rest in sheltered areas or below effective wave base and there formed tight, aphanitic limestone or the matrix of calcarenitic carbonate rock.

During Callovian to early Kimmeridgian time, the Tethys was a broad shallow sea depositing clastic limestone from central Arabia east to Iran and Oman and south across Yemen and the Aden Protectorates. Similar neritic limestone extends north through central Iraq. In these areas extensive calcarenite formation and abundant remains of shallow-water organisms attest to the fact that shoaling of the sea floor was widespread and persistent.

Perhaps the most significant facies change occurs in central Iraq where the upper part of the Callovian(?) is represented by massive anhydrite. This change is of particular importance for it marks the beginning of evaporite conditions that were eventually to spread over much of the basin of deposition. It is assumed that conditions essential to the precipitation of calcium sulphate—restricted basin where evaporation exceeds precipitation and runoff—obtained first over central Iraq and then spread progressively south to include Kuwait. Here, massive salt is interbedded with subordinate amounts of anhydrite. Deposition of evaporite in Saudi Arabia did not begin until near the end of early Kimmeridgian time.

With the approach of evaporite conditions, the Tethys shoaled, and widespread deposition of calcarenite began. In addition to covering much of Saudi Arabia, calcarenite deposited at this time has also been recognized in southwestern Iran, Qatar, and Oman. Essentially equivalent current-washed deposits may occur elsewhere (for example Yemen and the Aden Protectorates), but available descriptions are too vague to be certain. The clastic limestone represents the transition from continuous carbonate deposition to precipitation of nearly pure anhydrite. It also initiated widespread cyclic sedimentation which resulted in four main cycles, each starting at the base with normal marine limestone and closing with an evaporite member. The sequence culminated with the deposition of a massive Tithonian(?) anhydrite over much of the area. Recognized in most wells so far drilled in Arabia and also present at Qatar and Bahrain, each anhydrite may represent separate expansions along a similar route from the north where a more-or-less permanent evaporite basin persisted.

Conditions sufficiently restricted to bring about precipitation of calcium sulphate occurred first over a broad lagoon generally including the area of outcrop and extending east over southern Hawar. The evap-

orite basin continued to expand, eventually blanketing the Arabian coastal area and extending at least as far east as southwest Iran. Presumably one or more of the incursions reached Oman where a limestone breccia-conglomerate occupies an equivalent stratigraphic interval. The breccia probably represents residual carbonate after removal of interbedded anhydrite. Major exposures of Upper Jurassic gypsum-anhydrite in northeastern Yemen and adjacent parts of the Aden Protectorates show that an arm of the saline basin(s) extended southwest into this area as well. Thicknesses of the evaporite-limestone sequence deposited here are similar to those found in wells near the Saudi Arabian outcrop.

In Saudi Arabia and Qatar, carbonate members introducing the four evaporite cycles are, of course, of prime importance because of their oil content. The lowest of these is by far the most important reservoir; it contains productive oil in eight widely scattered fields.

Owing to intense interest prompted by oil search, enough data are now available to reconstruct, on a regional scale, conditions associated with the deposition of the lower limestone member. The general picture to emerge is that of sedimentation on a broad shelf. On the west, bordering the present area of Upper Jurassic outcrop, mainly clean-washed calcarenite and calcirudite accumulated. Presumably these mud-free deposits record littoral and near-littoral deposition around the edges of a carbonate-covered platform. Presence of wide belt of generally finer calcareous sediment immediately to the east suggests lagoonal conditions. The lagoonal sediments are in turn limited by a relatively unbroken sheet of clean calcarenite that blankets northern Ghawar-southern Abqaiq and extends north probably as far as Manifa.

These lime sands are interpreted here as representing an offshore bar, or more likely, a group of offshore bars. The absence of reefs cannot be assumed from the present widely scattered data, although the marked lateral continuity of individual beds, uniform thickness of the unit, and uniform sorting of the component grains suggest that large features of this type are not likely to be found. Calcarenites here, as well as those near outcrop, contain abundant dasycladaceous algae which certainly mark widespread and persistent shoaling of the sea floor into the zone of vigorous photosynthetic activity. The more muddy limestone of the Dammam-Qatif-Bahrain area is presumed to have been deposited in water of deeper but unknown depth. It is tempting to think that this area lay slightly east of the mud line of the time; however, regional considerations indicate that these sediments collected in a rather localized depression.

Carbonate deposition closed earlier in the west where precipitation of anhydrite first began. Saline conditions moved progressively east and eventually terminated carbonate sedimentation over most of the Persian Gulf area.

The same general carbonate-evaporite cycle was to be repeated at least three more times before the close of the Jurassic and open marine conditions again prevailed.

LOWER EARLY CRETACEOUS

With the influx of fresher water and termination of anhydrite deposition, shallow-water clastic limestones were once again deposited—limestones which are generally indistinguishable from those laid down during the Late Jurassic. These early Lower Cretaceous rocks maintain a high degree of uniformity over much of the foreland area. Particularly noteworthy is the lateral extent of some of the calcarenite units which must have been deposited literally as great sheets of lime sand. One such Berriasian lime sand can be traced from Khurais to the Persian Gulf and from the southern end of Ghawar into Kuwait and Iraq. Even though continuity over the entire area is not proved, concentration of sand on this scale must assuredly reflect a huge, remarkably flat, submarine platform only just below sea level. Although calcarenite is the most striking lithologic component, the larger part of the Berriasian and Valanginian section is aphanitic limestone and calcarenitic limestone.

Similar neritic carbonates occur in the central Rub' al Khali, Qatar, Oman, coastal Iran, Kuwait, and central Iraq. More basinal calcareous mudstone and radiolarian shale, marl, and limestone cover eastern Iraq. Presumably these indicate approach to the deeper part of the basin. The axis of the Tethyan trough at this time apparently fell near the northeast border of Iraq and extended southeast into Iran along the Zagros Mountains.

Early Lower Cretaceous rocks do not occur along the southern margin of the Arabian Peninsula. The limitation may, however, be the result of truncation rather than nondeposition. Berriasian and Valanginian rocks are, for all practical purposes, eliminated south of lat. 20° N. by pre-Hauterivian erosion. What is probably an equivalent and still active surface of unconformity is recognizable far to the south.

UPPER EARLY CRETACEOUS

The upper Early Cretaceous shows rather marked paleogeographic differentiation. The thin basal limestone so persistent on outcrop gives way to shale only a short distance downwind, and this facies prevails over much of the coastal area. The overlying continental, deltaic, and lagoonal sandstones grade east-

ward into limestone. Sandstone occurs in western Jordan, western Iraq, Yemen and the western part of the Aden Protectorates, as well as in Saudi Arabia.

The eastern boundary of the area where sandstone is dominant follows approximately the Tigris River north of Baghdad, passes close to Basra, just east of Kuwait, west of Safaniya and Abu Hadriya, across northern Ghawar, and thence trends south toward Al Mukallā on the Arabian Sea. To the east, across Oman and the Persian Gulf, neritic, and possibly some deeper water, limestone dominates. Shale, commonly dark, is dominant and transitional between sandstone and limestone in a thin band, in general including northern Ghawar, Fadhilli, Abu Hadriya, Khursaniyah, Manifa, Safaniya, Basra, and probably some parts of eastern Iraq. Radiolarian marl, shale, and limestone occur along the eastern border of Iraq and suggest basinal conditions prevailed in the area. Other radiolarian limestones of this age are known in northern Oman. The axis of the Hauterivian to Aptian basin reproduces that of the lower Early Cretaceous, the deeper part falling near or just beyond the north-eastern Iraq boundary and along the Zagros Mountains of Iran.

In summary, deposition of a thin Hauterivian carbonate-shale was followed by widespread emergence. Continental and transitional continental-marine conditions obtained in the west over a belt almost 200 to 300 km. wide that extends from Yemen to northern Iraq. To the east, normal marine limestones and shales were deposited on a shelf gently sloping into the deeper part of the basin. Maximum subsidence, along a northwest-southeast trend, occurred in southwestern Iran and near northeastern Iraq. There is some indication that subsidiary but large depressions existed west of the main basin.

MIDDLE CRETACEOUS

As seen on outcrop, Middle Cretaceous rocks are mainly sandstone with interbedded shale, at least in part marine in the central and northern area, and probably nonmarine in the south. The iron content of the rocks gives relatively strong colors in contrast to the unoxidized drab colors that prevail in coastal well sections, where the series falls naturally into two lithogenic units.

The upper unit of the coastal sequence, probably the time equivalent of the thin marine-nonmarine beds cropping out in the interior, is usually shale and limestone with little sandstone. The lower unit, primarily sandstone with subordinate shale, is a thick, widespread complex of deltaic, littoral, and other shallow-water deposits. Similar alternating sandstone and shale reflecting a fluctuating shoreline also occur

in Qatar and Bahrain. Shale begins to predominate over sandstone in an easterly and northerly direction. The clastics extend north into Kuwait, where sand is still dominant, and on into southern Iraq where shale is the major constituent. Sand is entirely replaced by limestone, anhydrite, and shale in northern Iraq. Beds of probable Albian age, equivalent to the lower unit of the coastal Middle Cretaceous, apparently are not exposed in central Arabia.

From such data it can be inferred that Cenomanian seas transgressed older beds and onto areas that were emergent during Albian time. Continued subsidence and oscillation of the shoreline led to deposition of thin marine stringers far up on the foreland. Greatest subsidence occurred from the latitude of Riyadh northward, bringing Middle Cretaceous across the beveled edges of progressively older units to eventually cap Lower Devonian strata in the vicinity of Sakakah. During this submergence, littoral and shelf sand, with rare thin carbonate intertongues, was spread over the northern area of Arabian outcrop; coarse clastics of probable marine origin continued downwind far enough to blanket Ma'qala' and Khurais and extended across the southern tip of Jordan and the southwest border of Iraq.

South of Riyadh, the marine sand grades laterally into continental deposits, still mainly sandstone. Presumably, the continental beds originally extended north to border the marine sands on the west. The nonmarine facies persists to the southern limit of exposures near Wādī ad Dawāsir. Even further south, in Yemen, it is quite likely that a thick continental-type Cretaceous sandstone includes equivalent beds, although this has not definitely been established.

East of the nonmarine beds and near-shore clastics, progressively more lagoonal and neritic section was introduced at the expense of the sandstone. Shale is the main rock type over a large area including the Rub' al Khālī and much of central and northeastern Arabia. Similar pelitic rocks probably extended into southwestern Iraq and southern Jordan. Further basinward, neritic limestone, in part in rudist reef facies and commonly *Orbitolina*-bearing, becomes dominant. Such shelf carbonates were deposited in a broad belt extending from southern Arabia to Jordan. More precisely, slow subsidence during Cenomanian and Turonian time permitted accumulation of shallow-water carbonate deposits over southern Arabia generally east of Al Mukallā and south of the Rub' al Khālī. The limestone belt continues north across the Oman Mountains, flares out to cover the Trucial coast, Qatar, Persian Gulf, and southwestern Iraq, and then swings inland to include Kuwait, southwestern Iraq, and most of Jordan. Even deeper water globigerinal

marls were being deposited at the same time in north-eastern and eastern Iraq. Presumably these continue into Iran, but proof of this is lacking.

In summary, widespread emergence of the Arabian foreland during the upper Early Cretaceous was followed by renewed subsidence in Cenomanian time. Northern Arabia was particularly active in this respect. Continued subsidence of the area between the central Arabian and Hā'il arches permitted widespread Cenomanian transgression over the beveled edges of older units.

UPPER CRETACEOUS

When viewed only in terms of Saudi Arabia, Upper Cretaceous paleogeography is relatively simple. Dominantly shallow-water carbonates blanket the area of outcrop, and deeper water shale and limestone come in as distance from the basin margin increases. Placed in the framework of adjacent areas, the picture becomes significantly more variable.

Emergence, possibly beginning in the Turonian, mainly affected coastal parts of the basin and isolated interior structures. Renewed transgression began in the Campanian and reached a maximum during Maestrichtian time. Marginal areas of the basin are defined by sandstones in southwestern Arabia, the Aden Protectorates, and Yemen. Presumably those sandstones in Yemen are exclusively continental, passing east and northeast through deltaic and shallow-water facies. Similar sandstones occur in northwestern Arabia near Sakakah and southern Jordan.

Along the southern fringes of the Rub' al Khālī, shale is the major lithologic component almost to the exclusion of all other rock types. Shale persists into the central Rub' al Khālī and coastal Arabia but is there confined mainly to the lower part of the Upper Cretaceous. The upper part (Campanian and Maestrichtian) is dominantly shallow-water limestone of the blanket type. Locally, rudistids as well as other heavy-shelled molluscs are abundant. The limestone sheet covers the central Rub' al Khālī, northern outcrop area, coastal Arabia and Qatar, Kuwait, southwestern Iraq, and Jordan. In Jordan, large amounts of chert are interbedded. In northeastern Iraq, and presumably southwestern Iran as well, more basinal conditions are reflected by the deposition of a thick succession of globigerinal marls.

Tectonic development during upper Late Cretaceous time also played a significant role in basin architecture and sediment patterns. Major uplift, generally along the northeastern side of the Zagros Mountains, contributed great volumes of flysch-like detritus to a long, linear trough rapidly developing on the southwest. Flysch-type sediments continued to pour in and gradu-

ally displaced the area of globigerinal marl sedimentation to the southwest.

In the Oman mountains, deposition of a thick radiolarite-chert series was followed by large-scale extrusions of ophiolite. Orogenic movements, initiating the formation of the now complex Oman geanticline, began during this time. Concurrently, volcanic activity apparently commenced in Yemen and the Western Aden Protectorate.

PALEOCENE AND EOCENE

Definite discordance between Cretaceous and Paleocene can be demonstrated in several areas adjacent to Saudi Arabia. Work with planktonic Foraminifera suggests equivalent hiatus in Arabia as well, although this has not been definitely proved. In any event, Paleocene transgression was widespread and resulted in a thick succession of neritic limestone and more basinal marls. Marginal sandstones of this epoch are unknown, carbonates alone being exposed along the landward edges of outcrop. Abundantly fossiliferous limestone documents Paleocene submergence of the southern half of the Arabian Peninsula generally east of long 47° E. One exception to this is the Oman Mountains where Paleocene and Eocene limestone overlaps both flanks of the range but does not reach the crest. Al Huqf itself was also incompletely covered although the remainder of the Oman-Dhufar foreland apparently was submerged.

North of lat 24° N., the belt of carbonate rocks, extending from Arabian outcrop to southwestern Iran, swings northwest and continues into Iraq. Most of Iraq was covered by globigerinal marl except near the northeast border. Here, flysch-type deposits accumulated in considerable thickness in a trough slightly offset southwest relative to the Late Cretaceous foredeep. Paleocene carbonate rocks also covered much of Jordan.

The Ypresian Age of the early Eocene witnessed the introduction of persistent and widespread evaporite precipitation. Anhydrite in considerable thickness was deposited over the Eastern Aden Protectorate and Dhufar, in the Rub' al Khālī basin, across Qatar, the western Persian Gulf, and northeastern Arabia and continued on into Kuwait and southern Iraq. Normal marine conditions prevailed in nearby areas except for red-bed deposition along the northeastern flank of the still subsiding Iraq-Iran trough.

Invasion of fresher sea water in the middle Eocene again brought about widespread deposition of carbonates, both nummulitic and globigerinal. For the most part, pre-anhydrite sedimentation patterns and overall distribution of carbonate were reestablished. In northeastern Iraq, however, clastic deposition ceased, and a carbonate-depositing sea once again covered the area.

MIOCENE AND PIOCENE

Widespread emergence of the Arabian platform in the middle Eocene reduced the Tethys to a relic sea, probably much as it is now. Since then emergence has persisted, and continental conditions have obtained over Saudi Arabia, with the exception of minor intermittent flooding of the present coastal area in middle Miocene time. The fauna of these marine beds indicate approximate correlation with the Lower Fars Formation of Kuwait, Iraq, and Iran. The Miocene sequence in Arabia probably represents in effect a thin wedge of lacustrine, fluvial, and coastal plain deposits peripheral to the main area of subsidence in Iran and Iraq where evaporite-forming conditions prevailed.

Marine sedimentation persisted in Iraq and Iran for a brief period following the Lower Fars evaporitic phase, but this was brought to a close with the start of large-scale deformation northeast of the main trough. Rising mountain folds shed great volumes of clastic debris into adjacent synclines—first red-bed (Upper Fars) material and then, with accelerated deformation, coarse sand and conglomerate (Bakhtiari). Combined thickness of these two units in some places reached as much as 4,000 m.

In spite of the intensity of diastrophism across the Persian Gulf, little trace of tectonic activity has been found in Arabia. In fact, rocks of presumed Pliocene (Bakhtiari) age have a low average dip of 1 to 2 m per km toward the Persian Gulf. How much of this is the result of tilting and how much is to be regarded as initial dip is unknown. Vast lava fields in the shield areas and in northwestern Arabia do attest, however, to considerable volcanic activity at this and later times.

With the Quaternary formation of great sand deserts and sheet gravels, the landscape of Saudi Arabia took on its present aspect.

CAMBRIAN AND ORDOVICIAN SYSTEMS

SAQ SANDSTONE AND EQUIVALENT UNITS—SIQ, QUWEIRA, UMM SAHM, AND RAM SANDSTONES

DEFINITION

The Saq Sandstone was named by H. L. Burchfiel and J. W. Hoover in 1935 for Jabal Sāq (lat 26°16'02" N., long 43°18'37" E.) where the upper part of the formation is exposed. As originally defined, the Saq was the lower member of the now obsolete Uyun Formation. R. A. Bramkamp raised the Saq to formal status in 1952; formal recognition followed in 1956 (Thralls and Hasson), and type section details were published in 1958 (Steineke and others). Outcrop suitable for detailed continuous measurement is lacking, and, as a result, only the upper part of the formation has been adequately described.

The type locality of the Saq Sandstone occurs along a traverse from the base of Jabal al Hanādīr (lat 26°27'24" N., long 43°30'11" E.) to Jabal Sāq (lat 26°16'02" N., long 43°18'37" E.) and then southwest to the Precambrian basement (lat 26°15'14" N., long 43°06'21" E.). Calculations indicate that more than 600 m of sandstone is exposed here.

So far as equivalent units in northwestern Arabia are concerned, the Siq Sandstone was first described and assigned formal status during preparation of U.S. Geological Survey Miscellaneous Geologic Investigations Map I-200 A (Bramkamp and others, 1963). The type section, just northwest of lat 28°00' N., long 36°00' E., is about 25 km east of Sha'ib as Siq, from which the formal name is derived.

The lower limit of the Siq is marked by obvious contact between Precambrian basement and sandstone; the upper boundary is not clearly defined. Much additional work needs to be done to properly define the vertical and lateral extent of this formation and to determine its relationship to overlying sandstone units.

Type localities of Quweira, and Umm Sahn, Ram Sandstones are in southwestern Jordan where they were measured and described by Quennell (1951). These formations were reliably traced southward into Saudi Arabia and mapped there by photogeologic interpretation. Although the Umm Sahn and Ram Sandstones could have been accurately separated, the two massive sandstone units were grouped for convenience and then traced on photographs into Arabia.

The base of the Saq and equivalent sandstones is at the sharply defined unconformity with the underlying crystalline complex. The top is at the contact between massive sandstone and overlying graptolitic shale (basal member of the Tabuk Formation).

OCCURRENCE AND THICKNESS

The Saq Formation and equivalent units crop out in a narrow band along the northern margin of the Arabian Shield. Except for a short sand-covered interval west of Hā'il, exposures are continuous from the latitude of Riyadh to the Jordan border, a distance of nearly 1,200 km. Width of the outcrop belt expands from a few kilometers at its southern limit to more than 100 km near the 39th meridian. The outcrop belt again narrows to the northwest and is only 30 km wide where it passes into Jordan.

The outcrop surface is a rough, hummocky plain which rises imperceptibly toward the basement complex. The plain is covered with erratic, wind-scooped basins and wind-sculptured hills, usually with low relief, although a few isolated, precipitous hills rise

abruptly from the plain. Jabal Sâq, 152 m high, and Jildiyah, 330 m high, are two of the more prominent features.

Thickness of the Saq, only a few meters near lat 24°22' N., uniformly increases to the northwest. At the type section thickness of more than 600 m is indicated by calculation. As fieldwork south and west of the Great Nefud is sparse, section thicknesses in that area are unknown. Quennell (1951) gives a composite thickness of 850 m for the Quweira, Umm Sahm, and Ram Sandstones at the type locality in southwestern Jordan.

LITHOLOGIC CHARACTER

Saq lithology is strikingly uniform both vertically and laterally. The dominant rock type is buff to gray and white, commonly crossbedded, poorly to well-sorted quartz sandstone that is often friable and commonly case hardened to a black, ferruginous quartzite surface. Color varies locally to mustard yellow or a pale brick red. In places a few thin partings of sericitic siltstone are present. Concentrations of iron along a well-developed set of north-south joints and a slightly less prominent set of east-west joints frequently produce low, spinelike ridges which stand a foot or two above the main rock surface.

At Jildiyah, 68 m of upper Saq is exposed. The section here is mainly off-white to purple, fine- to medium-grained, poorly indurated, subrounded, well-sorted quartz sandstone with streaks of quartz pebbles. Some intervals weather brown to black to red black, and many are casehardened. The sandstone is strongly crossbedded throughout and extensively jointed in two directions approximately at right angles to each other. A clean contact between the Saq Sandstone and overlying Hanadir member of the Tabuk Formation is exposed at Jildiyah. At Jibâl at Tawâl, to the northwest, about 120 m of Saq is exposed; it is chiefly white to purple to yellow, fine-grained, semifriable, massively crossbedded sandstone and is capped by beds of the Tabuk Formation. Sandstone with the same characteristics of crossbedding and peculiar weathering persists southward to the featheredge of Saq outcrop.

West of Jibâl at Tawâl, Saq outcrop is obscured for a short distance by Nafud sand cover. As a result, direct outcrop connection between Saq and equivalent units to the west has not been observed. However, there is little doubt regarding equivalency for Saq, and overlying Tabuk units can be traced without break around the sharpest part of the Hâ'il arch. In addition, there is substantial evidence that the Hâ'il arch is a relatively recent feature and apparently does not affect Paleozoic sedimentation patterns.

West of An Nafid the upper part of the Umm Sahm and Ram is buff, light-gray, red, and brown, weathering

to dark-brown and purple, crossbedded sandstone with common quartz pebble zones and locally interbedded red, ferruginous, sandy shale. The lower part consists of buff, tan, purple, massive quartz sandstone. Presumably continental in the lower part, thin lenses of purple shale with *Crusiana* indicate that the upper part is at least partly marine. Further west, near Harrat al 'Uwayrid, lenses and nodules of secondary chert, hydrated iron, and manganese oxide are common. In this area, the upper sandstone weathers to pinnacles and spires (Umm Sahm terrain). Below, a cliff-forming, eolian crossbedded sandstone (Ram terrain) is intricately jointed and on weathering forms bosses and stacks having vertical and overhanging walls.

NATURE OF CONTACT WITH ADJACENT FORMATIONS

The Saq Sandstone lies with marked unconformity on a mature surface of Precambrian crystalline rocks. The contact has been observed at several localities, although it is usually obscured by a cover of white quartz gravel. Where the contact can be seen, the basal Saq is conglomeratic, containing boulders, cobbles, and pebbles derived from underlying basement rock. The conglomeratic bed shows steep dip in several places, but whether the dip is a result of initial depositional processes or subsequent basement tilting is unknown.

The basement surface on which sedimentation first began is remarkably flat—a peneplain in the strictest sense of the word. East and southeast of Hâ'il, erosional relief seldom exceeds 10 m. Here the surface dips uniformly northeast under the sedimentary blanket at a rate of approximately 1.5°. The few observations that have been made west of Hâ'il indicate that the peneplain extends across this area and on into Jordan as well.

Throughout almost the entire length of outcrop, the upper Saq limit coincides with a sharp lithologic and topographic break between massive cliff-forming sandstone below and soft, easily eroded shale above. The contact, apparently gradational, persists from Jordan to just south of lat 26°00' N., where pre-Permian erosion eliminates the overlying shale and brings Upper Permian limestone into unconformable contact with the Saq. Southward, pre-Permian truncation cuts progressively deeper into the Saq and, near lat 24°22' N., has completely eliminated the formation.

PALEONTOLOGY AND AGE

Age of the Saq Sandstone, previously published as Cambrian(?), has been revised to Cambrian and Ordovician. The unit, in Saudi Arabia, is essentially barren although tracks of questionable trilobite origin were discovered at Safrâ' Haqil as early as 1947. They were also observed on the slopes of Jabal Sâq and in other localities northwest. Later, similar molds and

casts were collected from the Umm Sahm-Ram sequence. The tracks, apparently confined to the upper part of the Saq and Umm Sahm-Ram sequence, occur in local thin lenses of red-purple shale. Some of these forms were forwarded to Preston E. Cloud, Jr., for identification. He referred the specimens (written commun., Oct. 6, 1960) to the genus *Cruziana* (considered to be tracks of arthropods) and identified *Cruziana* cf. *C. furcifera* d'Orbigny and *C. huberi* (Meunier) of probable Early Ordovician age (about Arenig of the British standard succession).

The lower part of the sandstone sequence (Saq and Quweira) can be assigned to the Cambrian with confidence. Near the Dead Sea in Jordan, a limestone-shale unit well up in the section contains Middle Cambrian trilobites. Thus, the Saq (Saq, Quweira, Umm Sahm and Ram equivalent) may well record Early Cambrian to Early Ordovician sedimentation.

ECONOMIC ASPECTS GROUND WATER

Throughout the vast outcrop area of combined Saq and Umm Sahm, Ram, Quweira, and Siq Sandstones only one significant concentration of population occurs; that is in the district of Al Qasim near lat 26°00' N. Here a number of wells withdraw water from the Saq aquifer.

Outside the area of outcrop, several settlements use water derived from the Saq. At Tabuk, an estimated 20 to 30 flowing artesian wells have been completed in the Saq within the last two years. Average depth of these wells is about 245 m, and water quality is reported as good. At Taymā', three wells, ranging in depth from 107 to 122 m, produce from the Saq. The static water level is 4.5 m, quality being about 1,300 parts per million of total dissolved solids. Elsewhere, there are a few widely separated, shallow, hand-dug wells whose productivity varies directly with the annual rainfall. These wells produce from Quaternary alluvium, and the water level fluctuates with the local rise and fall of the water table.

ORDOVICIAN, SILURIAN, AND DEVONIAN SYSTEMS TABUK FORMATION—LOWER ORDOVICIAN TO LOWER DEVONIAN DEFINITION

R. A. Bramkamp and others (unpub. data) in 1954 proposed the name Tabuk Formation to include the thick sequence of sandstone, siltstone, and shale cropping out in the vicinity of Tabuk (lat 28°23' N., long 36°34' E.). The Tabuk at that time included all beds between the Saq Sandstone and the coarse, crossbedded sandstone of the Tawil Formation. Following formal definition of the Tabuk and Tawil Formations by Steineke and others (1958), new field work resulted in

an increase in Tabuk Formation thickness and inclusion of the overlying Tawil Sandstone as a member within the Tabuk Formation.

The name Tawil Sandstone was originally proposed in 1944 by E. L. Berg and others to include the more than 200 m of section exposed in the north-facing escarpment of At Tawil (lat 29°29' N., long 39°30' E.). Unfortunately, neither the upper nor lower parts of the unit are exposed at the type section. The lower contact was designated concurrently with establishment of the Tabuk type section, nearly 250 km west of At Tawil. The upper limit was defined by work in the vicinity of Al Jawf (about 60 km northeast of At Tawil) where the Tawil-Jauf contact is clearly exposed. When aerial photography became available in 1958, the Tawil outcrop was photogeologically mapped where possible, and, in recognition of type section shortcomings, a more complete sequence at Ash Shā'ib (lat 28°59'28" N., long 37°06'42" E.) was designated a reference section. At the same time, the Tawil was reduced to member status, for both field and photogeologic work indicated accurate separation from older beds of similar lithology was possible in only a few places.

The basal 104.9 m of the Tabuk type section as now defined (pl. 3) was measured on a traverse between lat 28°33'12" N., long 36°03'17" E. and lat 28°34'10" N., long 36°14'33" E. To the east, an estimated 212.7 m of section is concealed by gravel cover. An equivalent interval was studied in a supplemental section southeast of Tabuk near lat 28°19'30" N., long 37°04'03" E. A minor structural disturbance prevents completely filling the gap, although there is good reason to believe that only a few meters at the top remain unmeasured. The succeeding 159.8 m was composited from exposures at two locations—namely, lat 28°21'00" N., long 37°07'00" E. and lat 28°21'12" N., long 37°05'24" E. Another 314.3 m was measured at lat 28°44'54" N., long 36°34'39" E., and the remaining 102.8 m of pre-Tawil beds was described in the vicinity of Ash Shā'ib at lat 28°59'39" N., long 37°02'36" E. A supplemental measurement for the upper 177 m (Tawil Member reference section) was obtained at lat 28°59'39" N., long 37°02'36" E. (31.0 m) and lat 28°59'28" N., long 37°06'42" E. (146.0 m).

The base of the Tabuk Formation is at the sharp contact between *Didymograptus*-bearing shale and underlying, coarse grained, crossbedded Saq Sandstone. The top is the apparently conformable contact of massive Tawil Sandstone Member with shale and limestone of the Jauf Formation.

OCCURRENCE AND THICKNESS

The Tabuk Formation crops out in four main areas separated from each other by the Great Nefud sand

belt. The first area, extending southeast from An Nafud, discontinuously exposes Tabuk beds from Baq'a' to Buraydah, a distance of 280 km. Available thickness data is limited to two sections, each composed from several measured increments. At Baq'a', the formation is slightly more than 700 m thick. So far as known, the thickness remains nearly constant to lat 27°00' N. Near this parallel the pre-Permian erosion surface intersects the Tabuk and, southward, progressively cuts deeper into the formation. At Buraydah, the remaining Tabuk passes under the Nafud ash Shuqayyiqah, and final Tabuk truncation takes place somewhere under these sands, probably near the southern edge.

Tabuk exposures, southeast of the Great Nefud, form a complex topography consisting of alluvium-filled basins and intervening plains. Topographic expression is controlled largely by extensive duricrust formation and gravels concentrated during a post-Eocene erosional cycle.

The second and most extensive Tabuk outcrop area, roughly rectangular in shape, extends from the western edge of the Great Nefud to the southern Jordan boundary. In this area (about 340 km long and 240 km wide) the Tabuk is for all practical purposes unmapped. Two sections, pieced together from isolated measurements, indicate that average formation thickness is between 1,000 and 1,100 m. These figures are in doubt, however, as the monotonous nature of the sediments often obscures exact correlation between individual sections. The picture is further complicated by some faulting and the fact that unconformities, not yet recognized, probably occur at several levels.

The Tawil Sandstone Member is exposed in a wide band along the northeastern margin of the area. Contact between Tawil and pre-Tawil beds is clearly marked along the southern edge of the Al Hufrah plain by a rough, irregular escarpment. West of long 38°00' E., the contact scarp breaks down and loses its sharp topographic expression. As a result, the Tawil exposed between Wadi Fajr and At Tubayq cannot readily be separated from underlying strata. This area is indicated on the "Geologic map of the Arabian Peninsula" (U.S. Geological Survey—Arabian-American Oil Co., 1963) by fractional symbol and approximate contact.

The extensive Tabuk exposure west of the Great Nefud forms a broad planar surface, in places broken by northwest-southwest structural ridges and drainage channels. Differential relief averages about 50 m, individual hills rising somewhat higher above the general ground level. In some areas, flat-lying, well-bedded sandstone is intricately dissected into mesa and butte topography, channels being controlled by local

structural trends. Alternating hard and soft clastics of the pre-Tawil part of the Tabuk weather to a relatively smooth surface in comparison with the rough, hummocky surfaces formed by the strongly crossbedded sandstones of the Saq below and Tawil Member above.

The third main Tabuk outcrop occurs at At Tawil where the upper part of the formation (Tawil Member) is exposed in a precipitous range of black sandstone hills, some more than 200 m high. West of At Tawil, the upper Tabuk is exposed in a sharply dissected area fringing the southern edge of the Al Busayt'a gravel plain.

The smallest area of Tabuk outcrop is a few kilometers northwest of Al Jawf where the Tawil Sandstone Member is exposed in the slopes of hills and scarps. Here the massive sandstone is protected by caps of resistant Cretaceous and Eocene limestone.

LITHOLOGIC CHARACTER

The pre-Tawil part of the Tabuk Formation consists essentially of two major types of cyclic deposits. The first is thin-bedded (less than 1 to 2 inches thick) sandstone, shaly sandstone, sandy shale, siltstone, and shale. Ironstone, hematite, and gypsum occur locally, usually representing authigenic mineralization along bedding planes. Color ranges from off white to light purple, buff, brown, and brick red. Vertical tubular structures, *Scotithus*, and worm trails(?) parallel to bedding planes are extremely common. The second type of cyclic deposit consists of relatively thick bedded, (usually more than 5 to 10 ft thick), variably cemented, massive sandstone that locally is normally crossbedded or gradationally bedded. Streaks of gravel-size grains (4 mm and larger), usually rounded quartz fragments, occur locally. Some units host *Scotithus*.

Because of the cyclical nature of the pre-Tawil, outcrop characteristics may be expressed in terms of thin-bedded and massive units only or with reference to thin-bedded, slope-forming units capped, underlain, or sandwiched by massive, ledge-forming sandstone units. Additionally, surface exposures of the massive sandstone units can be described in terms of weathering characteristics—that is, "pinnacle" or rounded "sugar loaf," mainly controlled by degree of induration and cementation (iron or silica) and high-angle fracture system.

The Tawil Member, on the other hand, is characterized by medium- to coarse-grained sandstone with common gravel and conspicuous large-scale crossbedding.

The type section of the Tabuk Formation affords one of the most complete and representative descriptions of Tabuk rocks (pl. 4, section 1, p. 110). The entire interval was pieced together from several sec-

tions within an 85 km radius of Tabuk. A complete Tabuk section was measured and computed between Tayma' and Al Huj approximately along long 38° 30' E. Poor exposures and complexly interbedded lithologic units make meaningful subdivisions difficult; however, five major rock divisions can be recognized (section 2, p. 112).

The most complete exposure of Tabuk beds south of the Great Nefud occurs in the Quşaybā' section approximately along lat 26° 55' N. (section 3, p. 113). The dominant lithology is crossbedded sandstone, shale, siltstone and complexly interbedded sandstone and shale. Occurrence of graptolites is widespread; and vertical tubular casts, *Scolithus*, are common. Three shale members within the section form roughly parallel escarpments near the top, middle, and at the base. Using these shales as dividers, the Quşaybā' section can be separated into six informal units. Although the middle and upper shales cannot be traced laterally with any degree of certainty, the basal shale (Hanadir member) can be recognized along the entire length of Tabuk outcrop.

A. F. Pocock and R. P. Kopp in 1949 measured a second set of sections across the Tabuk just south of the Great Nefud. The line of traverse ran generally between Jildiyah and Ash Shu'aybah (section 4, p. 113). At this latitude four main subdivisions were recognized, including an upper sandstone unit that may be equivalent to the Tawil Member further northwest.

What is possibly an igneous plug intruding Tabuk strata was observed during the photogeologic delineation of formation contacts. Although the "plug" (near lat 27°30' N., long 37°00' E.) has not been visited on outcrop, the central, presumably igneous core, is characteristically weathered and fractured. Radial drainage is well developed on beds dipping sharply away from the "intrusive" mass. If this feature is, in fact, an igneous plug, it is the only such occurrence known within the sedimentary area of Saudi Arabia.

An experimental study to determine the usefulness of heavy minerals for correlation within the Saq-Tabuk complex was completed in 1961. The survey indicated that index minerals were present in sufficient number and variety to permit some regional correlation. As the study was concerned mainly with Tabuk zonation, the results are summarized here. The more important generalizations include:

1. Abundant heavy minerals having distinctive character and frequency were recorded for each formation sampled.
2. Type and frequency of heavy minerals alternate in direct response to changes in sediment texture—

that is, with cyclic deposition of thin-bedded, fine-grained sandstone-siltstone and thick-bedded, coarser grained sandstone-gravel.

3. A "stable" heavy-mineral suite consisting of zircon, rutile, B-tourmaline, G-tourmaline, and indicolite is common to all samples analyzed.
4. With the exception of certain authigenic index minerals, all heavy-mineral suites were derived from preexisting, sedimentary deposits. Accordingly, the provenance of these sandstones consisted of yet older sandstones and(or) unconsolidated sediments.
5. The sandstones sampled yielded fractions of very fine sand and silt. These provided most of the usable heavy minerals.

Petrological descriptions summarizing the analytical results for each formation studied follow.

Aruma Formation (sandstone facies).—In the eastern part of At Tubayq, Upper Cretaceous Aruma sandstone unconformably overlies the Tawil Member of the Tabuk Formation. Essential Aruma minerals include quartz with an accessory heavy-mineral suite consisting of apatite, biotite, chlorite, rutile, titanite, tourmaline, zircon, black opaques, brown resinous opaques, and the index mineral apatite-H. Frequent occurrence of apatite-H characterizes the Aruma Formation.

Apatite-H is colorless and euhedral, having extremely well developed hexagonal bipyramids and basal pinacoid or thin hexagonal prism plates. Because basal hexagonal sections are optically isotropic, an exact mineral species identification has not been made.

Tawil Member.—Essential minerals include well-rounded quartz grains and an accessory heavy-mineral suite consisting of apatite, biotite, muscovite, chlorite, rutile, titanite, tourmaline, indicolite, zircon, leucoxene, black opaque authigenic aggregates, D-anatase-X, and D-anatase-Y. High-frequency presence of D-anatase-X and D-anatase-Y is characteristic of the Tawil Member.

D-anatase-X is green or brown, thick, tabular, worn euhedral crystal fragments of anatase.

D-anatase-Y is light-yellow and brown, thick, tabular, worn, euhedral crystal fragments of anatase. D-anatase-Y exhibits a striking geometric patterning significantly different from that of D-anatase-X.

Tabuk Formation (pre-Tawil).—The essential minerals include fine-grained and silt-sized quartz particles with possible presence of several clay minerals. The pre-Tawil part of the Tabuk hosts a clearly identifiable mineral suite consisting of apatite, biotite, chlorite, muscovite, rutile, tourmaline, indicolite, zircon, leucoxene, authigenic aggregates, and A-anatase. High-frequency presence of extremely well developed A-anatase serves as an index mineral for the thin-bedded Tabuk sandstone units. Locally there is a high frequency

occurrence of sericite. Tawil-type sandstone (massively crossbedded) is intercalated with thin-bedded sandstone in certain parts of the pre-Tawil section. Where this occurs, proportion of A-anatase to D-anatase-X increases with descending stratigraphic position.

A-anatase is colorless, light-green or light-brown, authigenically zoned, thin, tabular euhedral crystal fragments predominantly restricted to the 0.062- and 0.031-millimeter fractions. A-anatase also occurs as crystal composites associated with authigenic aggregate material.

Sag Sandstone and equivalent units.—The essential minerals include medium- to coarse-grained quartz particles and an accessory heavy-mineral suite consisting of biotite, muscovite, rutile, tourmaline, zircon, leucogene, A-tourmaline and D-anatase-Z. These heavy minerals separate the Sag Sandstone from the overlying Tabuk by a relatively impoverished heavy-mineral content, and a high-frequency ratio of zircon with the presence of D-anatase-Z and A-tourmaline.

D-anatase-Z is yellow, reddish-brown, corroded, worn, sometimes euhedral fragments of octahedral crystals. D-anatase-Z exhibits a persistently worn, octahedral form which distinguishes it from D-anatase-X and D-anatase-Y.

A-tourmaline is light- to dark-green, highly rounded to subhedral crystal grains of tourmaline exhibiting extremely well developed to fairly well developed authigenic terminations. The fragility of the authigenic terminations precludes any development other than Sag in situ.

NATURE OF CONTACT WITH ADJACENT FORMATIONS

Throughout the length of Tabuk exposure, the base of the formation is marked by sharp but apparently conformable contact between graptolitic shale above and massive, crossbedded Sag Sandstone below.

Tabuk relationship to overlying units is considerably more complex. In two areas west of the Great Nefūd—Al Hūj and Al Jawf—the contact is conformable and upper Tabuk is directly overlain by Jauf Formation shale. Elsewhere, upper Tabuk beds are missing or covered. In southern Jordan and along the northern edge of At Tawil, Cretaceous and Tertiary units cut across strike to overlap the entire Tabuk sequence. However, a down-dropped block near Umm Nukhaylah has preserved a small patch of Jauf and Tawil, possibly in conformable sequence.

Southeast of the Great Nefūd, Tabuk is in apparently conformable contact with Jauf limestone as far south as lat 27°40' N. At lat 27°10' N. the Jauf has been removed, presumably by pre-Permian erosion, and Khuff Formation limestone (Upper Permian) rests

directly on Tabuk. The Tabuk itself is cut out somewhere under the Nafūd ash Shuqayyiah.

PALEONTOLOGY AND AGE

Steineke and others (1958) considered the age of the Tabuk Formation to be Ordovician and Silurian. Fossils discovered since that time indicate the upper part is Lower Devonian. A summary of the criteria upon which present dating is based follows.

Ordovician.—The lowermost part of the Tabuk Formation (Hanadir member) is characterized by the common occurrence of graptolites. Graptolites collected in 1947 were identified by A. A. Weymouth as *Didymograptus* cf. *D. bifidus* Hall. In 1960 Reuben J. Ross, Jr., U.S. Geological Survey, reidentified the same specimens as *Didymograptus protobifidus* Elles. Wide lateral persistence of this fossil serves to date the lower part of the Tabuk Formation as Lower Ordovician (Arenig). *Diplograptus*? sp. and *Climacograptus* cf. *C. brevis* Elles and Wood, of Upper Ordovician age, occur near the middle of the formation.

Silurian.—Several samples collected from the Tabuk, but without specific locality information, were identified by Reuben J. Ross, Jr. (written commun., 1961), as definitely Silurian on the basis of contained *Monograptus*. Other graptolites and some pelecypods also suggest a Silurian age although, in this case, other periods are not precluded.

Devonian.—A single collection from about 500 m above the Tabuk base consisted of molds of brachiopods, pelecypods, and gastropods. With regard to the gastropods, Ellis L. Yochelson, U.S. Geological Survey (written commun., 1961) states, "The seven gastropod specimens are all referred to the genus *Plectonotus*. To the best of my knowledge, *Plectonotus* is limited to the Devonian * * *". The pelecypods and brachiopods also tend to give a general impression of Devonian according to J. T. Dutro, Jr., and Ellis L. Yochelson (written commun., 1961).

As brachiopods from the upper part of the overlying Jauf Formation have been tentatively determined as Lower Devonian by G. A. Cooper, U.S. National Museum, it is likely that the upper one-half of the Tabuk can be assigned to this epoch.

A comprehensive listing of Tabuk Formation fossils includes: *Bollia* sp., "*Camarotoechia*", *Coelospira*?, *Levenea*?, *Lingula*, *Machaeraria* (cf. "*Rhynchonella*" *formosa* Hall), *Amplexograptus*?, *Climacograptus* cf. *C. brevis* Elles and Wood, *Climacograptus* sp., *Didymograptus protobifidus* Elles, *Diplograptus*, *Glyptograptus* sp., *Monograptus*, *Orthograptus* aff. *O. calcaratus* Lapworth var. *priscus*, *Rastrites*, *Colpomya*?, *Endoceras*?, *Goniophora*?, *Modiomorpha*?, *Orthoceras*, *Paleoneilo*?,

Plaesiomya?, *Plectonotus*, tracks and burrows [*Scolithus* (= *Tigillites*), *Arthropycus*, *Cruziana*].

ECONOMIC ASPECTS

GROUND WATER

West of the Great Nefud, ground-water potential of the thick Tabuk clastics is virtually unexplored. Considering its wide lateral extent, comparatively few watering spots exist, although there are shallow, hand-dug wells at Bi'r Fajr, Al Qalibah, and Taymā'. Some local water has been developed in the "Tabuk Valley" along the route of the abandoned Al Hijāz railroad. Agricultural development is notably lacking except for limited areas in and near the city of Tabūk.

Population concentration in the Al Qasūn region (near lat 26°00' N., long 44°00' E.) has resulted in extensive water search. An estimated 300 flowing artesian wells produce appreciable quantities of water from Tabuk aquifers. Similar agricultural sites are found at Qusaybā', Al 'Uyūn, Baq'a', Al Quwārah and Ash Shu'aybah. The prime water source in these areas is local hand-dug and shallow drilled wells, all producing from alluvial fill. Water accumulation in alluvium of larger channels and depressions varies with annual rain fall. At Buraydah and 'Unayzah, increased rain and consequent flow through Wādī ar Rimah is immediately reflected by higher water levels in the local wells. The water in this area, although plentiful, is extremely variable in quality and is commonly restricted to agricultural use because of high iron concentration.

DEVONIAN SYSTEM

JAUF FORMATION—LOWER DEVONIAN

DEFINITION

The Jauf Formation was named by E. L. Berg and others (unpub. data) in 1944 for the town of Al Jawf (lat 29°49' N., long 39°52' E.) near where the entire formation is exposed. The formation was originally defined by generalized section measurements in the vicinity of Al 'Abd syncline, 15 km northwest of Al Jawf, but detailed plane-table mapping by A. F. Pöcock and others in 1950 resulted in a substantially improved measurement and description. To obtain a complete succession these geologists pieced together 10 isolated measurements within a 30-km radius north and west of Al Jawf. The resulting composite (pl. 4) was adopted as the type section by Steineke and others (1958). The type locality remains as published except for addition of 27.1 m of calcareous shale and sandstone at the top. Previously these beds were considered to be of Wasia (Middle Cretaceous) age; but Devonian fossils were recently discovered, and the unit is now included with the Jauf.

The base of the Jauf Formation is at the contact between lower Jauf shale and silty limestone and underlying crossbedded sandstone of the Tabuk Formation (Tawil Member). The top is at the unconformity between fossiliferous Jauf limestone and overlying siltstone and sandstone of the Sakaka Sandstone (Wasia Formation).

OCCURRENCE AND THICKNESS

In comparison with other Arabian units, Jauf exposures are small. Significant outcrops occur only in three areas. The first is around Al Jawf where the complete sequence is cleanly laid out. Here, the formation forms a series of northwest-southeast escarpments, each with a scree-covered face of soft, silty shale capped by a thin bed of flat-lying limestone.

The scarps are generally less than 50 m high although some are as much as 100 m high. The few sandstone units present commonly form moderate ledges in the scarp faces, but are not sufficiently resistant to support large mesas. Structural events have seriously disrupted areas of Al Jawf exposures, and fault and flexure scarps are everywhere conspicuous.

In the region of Al Hūj (lat 29°00' N., long 38°30' E.), Jauf exposures form a northwest-trending rectangle roughly 40 by 80 km. Here, flat-lying beds form conspicuous scarp and bench topography and a few isolated hills. At places the beds are disrupted by tensional faulting and isolated down-dropped blocks.

Main Jauf exposures in Najd (east of long 42°) form two parallel escarpments, Jāl al Haylā' and Jāl ash Shu'aybah. Each scarp, capped by a thin bed of resistant dolomitic limestone, has an average relief of less than 20 m along the entire 50 km of outcrop. Jauf exposures, in the bottom of channels, can be traced south from the escarpments almost to lat 27°25' N. where Quaternary duricrust completely covers the formation.

Formational thickness ranges from 185 m in Najd to about 300 m at the type locality. A 206-m section was measured at Al Hūwāt in the Al Hūj region. Reduced thicknesses occur in other areas where pre-Cretaceous and younger erosion cycles have removed upper Jauf beds.

LITHOLOGIC CHARACTER

The lithologic character of the Jauf Formation changes little throughout the area of outcrop. The few complete sections that have been measured indicate that the unit is mainly varicolored silty shale. Numerous thin beds of limestone and dolomite occur in the upper one-third of the formation, and a few carbonate stringers are present near the base. Very thin beds of fine-grained sandstone occur at several levels. Data from the three complete sections so far measured indi-

cate that, on the average, about 50 percent of the formation is silty shale, 25 percent is sandstone, and the remainder, carbonate. Significant variations in shale to sand ratio between sections do occur, and these are, no doubt, related to lensing and complex interbedding.

One of the most accessible and best known sections of the Jauf Formation is that pieced together in the vicinity of Al Jawf (pl. 4). As this section was measured in detail and later designated as the type locality, a complete description is given in section 5 (p. 113).

A complete Jauf sequence (section 6, p. 115) was measured in the vicinity of Al Halwāt (lat 28°50' N., long 38°42' E.). The so-called transition beds of the type section as well as the upper part of the Hammamiyat member are apparently missing, owing to pre-Wasia erosion. Although some facies changes are evident, lower units are still recognizable.

Cursory examination of Jauf Formation exposures in the At Ṭubayq-At Ṭawil plateau region suggests that the gross lithologic features of the type locality extend into this area as well. Some variations within members were observed; however, on the basis of the limited data available they do not seem significant enough to warrant separate description.

A. F. Pocock and R. P. Kopp were the first to recognize Jauf exposures southeast of the Great Nefud. Although 185 m of section was measured near Ash Shu'aybah, the sequence is incompletely known, for Naḥḍ sand and other late sediments mask the upper and middle parts. Described lithologic components include red-brown, impure dolomitic limestone and gray-green, gypsiferous, silty shale in the lower 30 m and white to gray, fine-grained, crossbedded sandstone with a 1-m limestone cap in the upper 85 m.

NATURE OF CONTACT WITH ADJACENT FORMATIONS

In all outcrop areas so far studied the Jauf Formation directly overlies Tabuk clastics. Definite evidence of discordance between the two units is lacking, although shift from continental (Tabuk) to marine (Jauf) sedimentation would presumably involve hiatus.

At the top, the Jauf is in unconformable contact with overlying units. Middle Cretaceous Wasia (Sakaka) sandstone caps Jauf exposures in the eastern part of the Al Jawf area, along the northwestern margin of the At Ṭawil plateau, and in isolated Al Ḥij hills. In other areas, such as the western part of the Al Jawf exposures, and north and west of At Ṭawil, pre-Late Cretaceous erosion brings Aruma Formation sandstone in contact with the Jauf.

Southeast of the Great Nefud, a single small exposure shows Upper Permian limestone resting on Jauf.

Elsewhere in this area Jauf beds are overlain by relatively recent duricrust and eolian sand.

PALEONTOLOGY AND AGE

Meager faunas have been collected from various levels in the Jauf Formation. Brachiopods in the upper part, including *Anathyris* and *Rensselaeria*, have been tentatively determined as Lower Devonian by G. A. Cooper. Uppermost beds have yielded ostracods and fish remains. *Knoziella* and fish dermal scutes were considered in 1960 by R. W. Morris, Aramco, to be definitely Devonian and probably Lower or Middle Devonian.

The lower part of the Jauf Formation was originally suspected to be Silurian. However, the discovery of Devonian (probably Lower Devonian) forms in the underlying Tabuk Formation precludes a Silurian age for any part of the Jauf. Thus the Jauf can be assigned a Devonian age with confidence and probably is Lower Devonian. A comprehensive fossil list includes: "*Bythocypris*" sp., *Knoziella* sp., *Anathyris*, *Lingula*, *Plectambonites*? sp., cf. *Pleurothyris*, *Rensselaeria*, *Schizophoria* spp., *Schuchertella* spp., *Schuchertella*? spp., *Spirifer* spp., indeterminate strophomenid brachiopod, *Cyathophyllum*? sp., *Favosites* (s.l.) sp., *Favosites*? cf. *Orthoceras*, *Tentaculites* sp., *Valcata*, crinoid stem fragments, spongiotromatids, crustacean and arachnid fragments, fish dermal scutes.

ECONOMIC ASPECTS

GROUND WATER

Jauf water potential is for all practical purposes unknown. Several wells have been drilled in the Al Jawf area, but information on these is lacking.

PERMIAN AND OLDER(?) SYSTEMS

WAJID SANDSTONE—LOWER PERMIAN AND OLDER(?) DEFINITION

The Wajid Sandstone was named in 1948 by R. D. Gierhart and L. D. Owens for Jibāl al Wajid. Here, the lower part of the type section (Steineke and others, 1958) was measured in a series of hills and mesas generally along lat 19°51' N. and between long 44°25' E. and 44°35' E. The upper part of the type section is exposed in the vicinity of Banī Ruḥayyah (lat 19°50' N., long 44°46' E.).

The base of the Wajid is at the nonconformable contact of sandstone with igneous and metamorphic rocks of the basement complex. The upper limit is placed at the disconformable contact between sandstone below and basal Khuff (Upper Permian) carbonate above.

OCCURRENCE AND THICKNESS

Wajid Sandstone is continuously exposed from Wādī ad Dawāsir (lat 20°30' N.) south almost to Najrān

(lat 17°35' N.), a distance of more than 300 km. The eastern edge of outcrop closely follows long 44°45' E.; the western margin is convex against Precambrian basement. Maximum outcrop width of 100 km is reached near the 19th parallel.

Smaller isolated remnants capping Precambrian basement occur to the southwest and extend into Yemen. In addition, part of the upper Wajid crops out at the base of the Banī Khatmah escarpment (lat 18°10' N., long 45°23' E.).

The main area of Wajid outcrop south of Wādī ad Dawāsīr forms a rather extensive pediment which maintains nearly the same gradient as gravel cover to the east. Isolated sandstone hills and dissected sandstone plateaus and mesas rise about 150 m above the pediment level. Spectacular hills occur at Banī Muṣayyirah, Banī Sanāmah, Jibāl al Wajid, and Banī Khurb.

Thickness of the Wajid for sometime was considered to be in excess of 300 m (Steineke and others, 1958). Calculations based on new data indicate maximum outcrop thickness may be as great as 950 m.

LITHOLOGIC CHARACTER

The intricately dissected Wajid plateau results from erosion of a remarkably homogeneous continental sandstone. Detailed measurement and description of the sequence has not been possible because of limited field work and lack of correlative marker beds. Lithologies characteristic of various parts of the section have been described from isolated localities, however, and a discussion of them follows.

The basal unit of the Wajid, a conglomerate immediately above Precambrian basement, has been studied near lat 19°30' N., long 44°00' E., where a typical sequence is clearly exposed. Here, the unit is 11 m of crossbedded sandstone and poorly consolidated, quartz gravel conglomerate.

In 1949, R. D. Gierhart and L. F. Ramirez measured 150 m of lower Wajid at Banī Sanāmah (near lat 20°15' N., long 44°18' E.). The interval is mainly lightgray, poorly to moderately sorted, crossbedded sandstone grading upward into a well-sorted, friable sandstone with some limonite and hematite concretions and a few dolomite fragments. Erratic bands of quartz-pebble conglomerate occur near the bottom, and thin quartzitic hematite bands are present throughout. A thin bed of white to tan sugary dolomite occurs near the top.

A 365-m section, representing middle Wajid, was pieced together in the south-facing scarp at Banī Khurb (lat 19°43' N., long 44°41' E.). The section is almost entirely sandstone, mainly poorly sorted, subangular, crossbedded, and friable. Many red and purple

hematitic bands and some thin quartzitic layers are included. Conglomeratic beds, some containing limestone pebbles, occur in the middle part.

In 1950, S. B. Henry and R. A. Bramkamp measured 120 m of Wajid at Khashm Khatmah (lat 18°10' N., long 45°23' E.) where the uppermost part of the formation is exposed. The upper 50 m is dominantly gray-green to red silty shale with subordinate, interbedded, tan to purple, fine-grained sandstone. White, poorly cemented, medium-grained sandstone with pink and white quartz pebbles occurs near the top. The lower 70 m is chiefly off-white to yellow, coarse-grained, poorly cemented, crossbedded sandstone. Erratics derived from granitic and metamorphic rocks occur in two zones—the lower, 30 m above the base, and the upper, about 70 m above. The boulders of basement rocks, commonly less than 1 ft in diameter, may be as much as 5 ft across. Continuous sand and gravel cover separates Banī Khatmah (upper Wajid) and Banī Khurb (middle Wajid) exposures. As a result, stratigraphic relationship between the two areas is uncertain, although lithologic similarity and position relative to overlying beds suggest at least partial equivalency.

NATURE OF CONTACT WITH ADJACENT FORMATIONS

Observations along the western margin of Wajid outcrop indicate that the Wajid Sandstone was deposited on a gently undulating basement surface. Invariably, a basal quartz conglomerate fills low areas and depressions; basement highs are covered by coarse-grained crossbedded sandstone.

Outliers of Wajid occur west and southwest of the main sediment-basement contact. The largest of these cap high mountains in the vicinity of Najrān and extend into Yemen. Few such isolated remnants have been visited, and, as a result, they are little known. Conversely, inliers of igneous rock have been observed as much as 10 to 15 km east of the main basement mass. At several places granite pedestals protrude through Wajid cover and rise several tens of meters above the surrounding sandstone. These inliers, in each instance capped by Wajid, are believed to represent presedimentation monadnocks. A striking example of such an isolated hill occurs at Hīmā (lat 18°14' N., long 44°27' E.) where a large outcrop of pink granite protrudes from the wādī floor and reaches the height of flanking sandstone valley walls.

Contact between Wajid Sandstone and overlying units is visible in only two areas. In the first, near lat 20°00' N., long 44°45' E., small patches of Khuff Formation (Upper Permian) limestone rest directly on Wajid. Although contact is certainly unconformable, it is not possible to determine whether angular discordance is involved. The second area of upper Wajid exposure

is in the west-facing escarpment at Banī Khaṭmah. Along most of the scarp, Khuff sandstone disconformably overlies Wajid shale. At Jabal al Qaṣbah, however, Tuwaiq Mountain Limestone (Upper Jurassic) has overlapped the Khuff and lies unconformably on Wajid. Alluvial cover prohibits tracing the contact much beyond Jabal al Qaṣbah, but bore holes far to the southeast still show Tuwaiq Mountain resting on Wajid.

PALaeONTOLOGY AND AGE

For many years, stratigraphic position afforded the only clue to the age of the Wajid Sandstone—that is, pre-Khuff and postbasement. Recently, a bore hole at Ash Sharawrah (lat 17°30' N., long 47°06' E.) recovered Lower Permian spores from beds probably equivalent to the upper Wajid of outcrop. Other southern Arabian wells have penetrated Lower Devonian through Carboniferous spore zones in strata that are probably, at least in part, equivalent to outcrop Wajid. Age of the Wajid Sandstone is therefore considered to be Lower Permian and older(?).

ECONOMIC ASPECTS

GROUNd WATER

Subsurface water potential is virtually unexplored except for a single penetration at Ash Sharawrah. The well at this locality was bottomed in the Wajid and now produces potable water from these sands.

PERMIAN SYSTEM

KHUFF FORMATION—UPPER PERMIAN

DEFINITION

The Khuff Formation was named for Khuff ('Ayn Khuff) (lat 24°55' N., long 44°43' E.) near the Riyadh-Jiddah road. As defined by Max Steineke in 1937, the formation included the lowermost carbonate sequence cropping out in central Arabia and was the basal unit within the Mustawī Group—a now discarded subdivision. Although the Khuff was first recognized in publication by Steineke and Bramkamp (1952b), it was not until later that the succession exposed near Khuff was formally designated as type section (Steineke and others, 1958).

The type Khuff was measured along a traverse southwest from lat 24°58'36" N., long 44°41'48" E. to lat 24°53'12" N., long 44°32'48" E. The base is at the unconformable contact between a lower sandy phase of the Khuff and the underlying massive sandstone of the Saq. The top is placed at the level where Khuff limestone and dolomite are in sharp contact with red and green gypsiferous shale of the overlying Sudair Shale.

OCCURRENCE AND THICKNESS

Khuff exposures can be traced from Banī Khaṭmah (lat 18°00' N.) north to the Great Nefud (lat 28°10' N.), a distance of more than 1200 km. Between the Great Nefud and Quṣaybā' (lat 27°00' N.), only small outliers of Khuff are exposed. These are isolated from the main outcrop area to the south by duricrust cover. From Quṣaybā' south to lat 21°30' N., the Khuff crops out in a nearly continuous band. Width of the outcrop belt throughout this distance (about 650 km) is amazingly uniform, averaging about 25 km. South of lat 21°30' N., the Khuff is exposed in patches isolated by Quaternary sand and gravel. In this area, the best and most persistent exposures occur in the Al 'Arid and Banī Khaṭmah escarpments.

Thickness of the Khuff Formation shows little variation when length of outcrop is taken into consideration. Five measurements between lat 27°00' N. and 24°00' N. recorded a minimum thickness of 235 m and a maximum of 292 m. South to Wādī ad Dawāṣir (lat 20°00' N.), some thinning is evident and the unit ranges in thickness from 195 to 230 m. The southernmost exposure of a full Khuff sequence (154 m) occurs in the Al 'Arid scarp near lat 19°00' N. The reduced sections (100 to 0 m) measured further south at Banī Khaṭmah represent truncated rather than true depositional thicknesses.

LITHOLOGIC CHARACTER

The lithology of the Khuff Formation changes gradually along strike. Generally north of lat 24°00' N., the section is characterized by a natural tripartite subdivision, the lower and upper parts being mostly limestone and the middle dominantly shale. South of the 24th parallel, distinction between the three units becomes less clear as the shale is largely replaced by limestone and much of the section is dolomitized. The Khuff, mostly limestone at lat 23°00' N., becomes progressively more clastic to the south. At the southern end of the Al 'Arid escarpment, the formation is almost exclusively in sandstone facies.

In 1945, R. A. Bramkamp and others measured and described in detail the Khuff section near Ar Rayn (lat 23°33' N.). Exposures are much more complete than at the type locality, and, as a result, the Ar Rayn measurement has been designated Khuff reference section (fig. 2). A complete description of the Ar Rayn sequence is given in section 7 (p. 115).

A three-fold division of the Khuff Formation was recognized (section 8, p. 116) at the type locality itself (near lat 24°56' N.) in the vicinity of Wādī Maghīb.

During 1948 and 1949, the Khuff was mapped northward from the type locality. At lat 26°30' N. the Khuff is partly obscured by duricrust, and no complete outcrop occurs north of this point. A. F. Pocock and

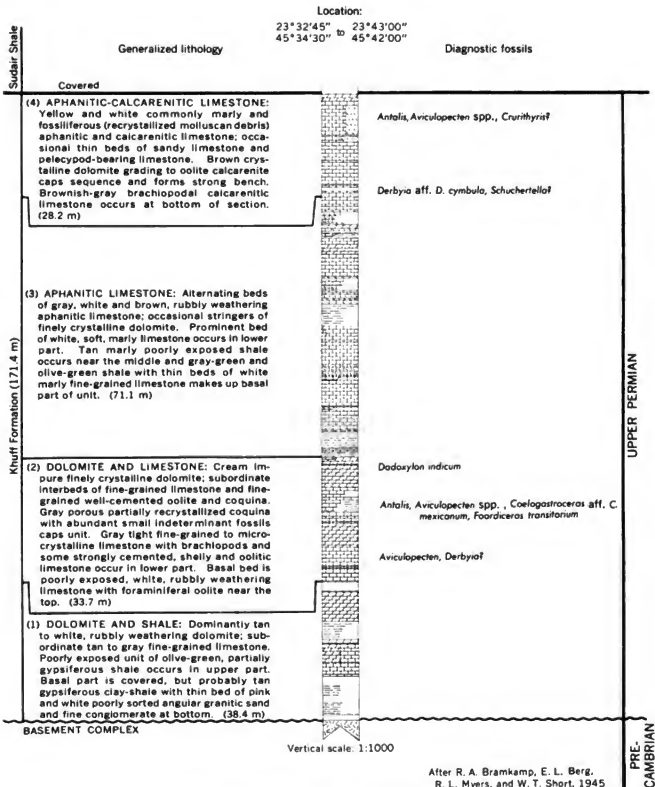


FIGURE 2.—Khuff Formation reference section.

R. P. Kopp pieced together a section as far north as Qaşaybā'; but much of the sequence is covered, and many of the interval thicknesses were calculated. The composite section indicated 255 m of Khuff with 76 m of Khartam limestone, 63 m of Midhnab shale, and 116 m of lower Khuff limestone.

Northern area Khuff is best characterized by the section exposed about 30 km north of Buraydah near lat 26°30' N. Here, Pocock and Kopp described an almost complete succession (section 9, p. 117).

South of the Riyadh-Jiddah road, the Midhnab shale passes laterally into carbonate. With loss of the shale separator, the three-fold subdivision can no longer be recognized at the Ar Rayn reference section. About 100 km south of Ar Rayn, other significant changes in Khuff lithology can be observed. Near Al Mulayb (lat 22°36' N.), sand and shale intertonguing with carbonate give the first hint of the complete replacement by sandstone that occurs farther south. R. D. Gierhart and others in 1949 traversed and composited the poor Khuff plains exposures in the Al Mulayb area; a summary of their description is given in section 10 (p. 117).

From Al Mulayb south to the Al 'Arid escarpment, a distance of about 350 km, the Khuff is largely obscured by surficial sand and gravel. Because of its low relief in this area, the Khuff probably is mostly shale and sandstone. Investigation of partial exposures west of Al Haddār (lat 22°00' N.) tends to confirm this assumption, and further support is offered by outcrops of basal Khuff clastics near lat 20°00' N., long 44°50' N.

At Al 'Arid, the Khuff sequence is not fully exposed at any one locality because of partial scree cover, but a complete section has been obtained by moving laterally along the scarp. In 1950, S. B. Henry and R. A. Bramkamp measured the upper and middle parts of the formation respectively 11 and 22 km south of Khashm Sudayr (lat 19°12' N.); the lower part was described by R. D. Gierhart and L. D. Owens in 1948 at Jabal Umm Ghirān (near lat 18°42' N.). A summary of this description is given in section 11 (p. 117).

A recent reconnaissance traverse near Unayzah (just south of Buraydah), revealed discrete evaporite units within the Khuff. The lowest unit, consisting of 6 m of gypsum, is 28 m above the base of the formation. A second bed of gypsum (4 m thick) is exposed some 90 m above the base. Two other thin beds of gypsum were also observed further south in the area of the type section.

The three major lithologic units identifiable north of the Riyadh-Jiddah road strongly influence Khuff topography. The lower Khuff limestone forms a prominent 20- to 40-m-high west-facing scarp, the back slope of which has been weathered to a series of well-developed

strike ridges. This feature—the Khuff escarpment—is the first of several distinctive benches to be seen in the region. The upper limestone supports a somewhat less prominent ridge—the Khartam escarpment. Between the Khuff (Safra' as Sark) and Khartam escarpments, the surface of the Midhnab member is characterized by a number of small, shinglelike benches. Each bench is supported by a thin carbonate bed in an otherwise comparatively soft gypsum-shale sequence. Taken as a whole, the Midhnab has been eroded into a broad asymmetric valley sandwiched between the two larger scarps. The valley is the site of numerous date gardens from Khuff to Buraydah. Sandstone and shale occur in the truncated Khuff section at Banī Khatmah.

NATURE OF CONTACT WITH ADJACENT FORMATIONS

Geometric relationships between the Khuff and underlying units suggest that epirogenic uplift and massive erosion preceded Khuff deposition. Regionally, it can be demonstrated that the lower Khuff contact is everywhere unconformable. From north to south the Khuff (1) rests successively on Lower Devonian through Cambrian(?), (2) is in nonconformable contact with Precambrian basement between lat 24°20' N. and 20°30' N., and (3) disconformably(?) overlies Wajid south of lat 20°30' N. The contact between Khuff and older sedimentary units is most commonly limestone on sandstone. In the general area where Saq Sandstone is overlain, however, the basal Khuff is a clastic usually sandstone-facies. South of the 19th parallel the contact is also sandstone on sandstone.

The top of the Khuff is sharply defined along most of the outcrop belt by conformable contact between limestone below and red and green Sudair Shale above. South of lat 19°00' N., Sudair is cut out and Tuwaiq Mountain Limestone (Upper Jurassic) rests unconformably on Khuff Sandstone. The pre-Tuwaiq Mountain erosion surface cuts progressively deeper into the Khuff until the formation is removed entirely near the south end of Banī Khatmah (lat 18°00' N.). There is little doubt that elimination of Khuff in northern Arabia is brought about by pre-Wasia truncation, although sands of the Great Nefud cover the area where this occurs.

PALaeONTOLOGY AND AGE

The Khuff Formation was considered by Steineke and others (1958) to be of probable Late Permian age. As the only diagnostic fossils found on outcrop had been a few poorly preserved nautiloids and brachiopods, some uncertainty was attached to this age assignment. Other fossils are not uncommon, but most are nondescript pelecypods and gastropods.

Microfossils derived from recently drilled wells support a Late Permian age for the Khuff. L. G. Henbest

in 1957 (written commun.) examined a Khuff core from Dammam well 43 (lat 26°20' N., long 50°10' E.). Several Foraminifera including *Colaniella parva*? (*Colani*) were identified. Henbest states "Permian is indicated with fair assurance. According to the present, rather meager knowledge of the range of *Colaniella parva*? (*Colani*) the lower part of the Upper Permian is indicated, but question even of Permian versus Pennsylvanian age must remain until this evidence is verified with other information."

Additional core material from well 43 was sent to Richard Rezak for study. He reported (1959) "Algal assemblage dates the Khuff Formation as late middle Permian or late Permian."

A shallow hole drilled in 1961 at the base of the Khuff escarpment (near lat 22°00' N.) yielded Upper Permian spores and pollen. Another Upper Permian (Thuringian) spore and pollen suite was collected in 1962 from a deep bore hole drilled near lat. 21°50' N., long 48°00' E.

On outcrop, the lower Khuff fossils (shown on fig. 2) were collected between 40 and 72 m above the base of the formation. Those listed in the upper Khuff were collected from 2 to 28 m below the formation top. Although the faunas of the lower and upper Khuff differ somewhat in species, the two assemblages are essentially similar generically. Both collections include genera that are not known to occur above the Paleozoic. A comprehensive listing of fossils collected from Khuff outcrop includes: *Crurithyris*? sp., *Derbyia* cf. *D. cymbula*, *Derbyia* spp., *Derbyia*?, *Meekella*? sp. cf. *Orthotetes*, cf. *Rhipidomella*, *Schuchertella*? sp., *Antalis*, *Antalis*?, *Aviculopecten* spp., *Bellerophon* spp., *Bellerophon*? sp., *Botulus*? sp., *Cardinia*? sp., *Circulopecten* sp., *Coclogastroceral* aff. *C. mexicanum* (Girty), *Cymopolia*, "*Dentalium*" sp., *Dimyopsis* sp., *Dimyopsis*? sp., *Foordicera transitroia* (Waagen)?, *Hyalolithes* sp., *Nautilus* spp., *Ozytoma*? sp., *Pleuromya*? sp., *Pleurotomaria*? sp., *Taenioceras*? sp., indeterminate pectinids, cerithiids, and laxonemids, *Dadoxylon indicum*, *Lepidodendron* sp., indeterminate amphineuran impressions, bryozoa, echinoid fragments, and ostracodes.

ECONOMIC ASPECTS

GROUND WATER

Shallow hand-dug water wells occur only sporadically through the area of Khuff outcrop. Villages in the northern area are concentrated along the Midhnaab shale trough where surface runoff from the lower Khuff limestone collects.

HYDROCARBONS

Few deep wells have penetrated the Khuff Formation, and petroleum potential of this unit has not

been fully evaluated. Some promise is indicated by the fact that gas has been found at several localities.

PERMIAN AND TRIASSIC SYSTEMS

SUDAIR SHALE—UPPER PERMIAN AND LOWER TRIASSIC

DEFINITION

The Sudair Shale is named for Khashm Sudair (lat 19°12' N., long 45°06' E.) where the lower part of the unit is well exposed. A complete discussion of the development of present-day Permian and Triassic nomenclature is included in the definition of the Jilh Formation (p. 35).

The Sudair was first separated out as a discrete unit in 1945 by R. A. Bramkamp, who designated it the lower member of the now obsolete Es Sirr Formation. In 1951, R. D. Gierhart and R. A. Bramkamp raised the rank of the Sudair to formation and established the Al 'Arid escarpment as the type locality. Formal publication followed in 1952 (Steineke and Bramkamp, 1952b), and the type section was described by Steineke and others (1958). The total type section (116 m) was pieced together from three measured sequences: the lower 27.1 m is exposed at Khashm Ghudayy (lat 19°17'42" N., long 45°06'27" E.), another 23.1 m was picked up 12 km further north (lat 19°23'23" N., long 45°08'00" E.), and the upper 65.8 m occurs at Khashm Abū Ramaḍah (lat 19°38'09" N., long 45°07'21" E.).

The base of the Sudair is placed at the top of a platy sandstone unit believed to be equivalent to the top of the Khuff Formation in its type section. The upper limit is at the contact between red Sudair shale below and Middle Jurassic sandstone above.

OCCURRENCE AND THICKNESS

There are few good exposures of the Sudair. However, original extent of the formation can be inferred from isolated outcrops and, in areas of cover, from the Sudair's characteristically depressed topographic expression. Using these criteria, the Sudair can be traced from lat 27°10' N. almost to lat 19°00' N., a distance of 850 km. Along most of its length, the erosional valley is flanked by more resistant units—the upper Khuff (Khartam) limestone on the west and lower Jilh sandstone and limestone on the east. Trapped Quaternary sand and gravel now fill much of the trough.

The northernmost outcrop of Sudair is in a small mud flat, Mudarraj (lat 27°10' N., long 43°43' E.). To the south, isolated remnants of lower Sudair occur in a thin band between the Nafūd as Sirr and Khuff limestone. Near the south tip of Nafūd as Sirr (lat 24°20' N.) the pattern shifts and only upper Sudair is exposed, protected in this case by the overlying Jilh

as far south as lat 23°45' N. Between lat 23°45' N. and 19°45' N., a distance of nearly 450 km, Sudair rocks are exposed only in small windows in Quaternary cover. Outliers of this type occur near Al Juwayfah. Al Haddaar, Khashm Mishlab, Khashm Taryam and Khashm Kumdah. The most southerly and best exposures of the Sudair are in the northern part of the Al 'Arid escarpment.

Poor exposure has permitted accurate measurement of Sudair thickness only in two places—near Buraydah and at Al 'Arid. Some idea of regional changes can be obtained, however, by supplementing these figures with calculated data. Generally speaking, the formation thins southward. A maximum thickness of 195 m was pieced together from exposures north of Buraydah; a minimum (116 m) was obtained at the type section near lat 19°30' N. An anomalous interval of about 180 m occurs between lat 22°00' N. and 23°00' N. Whether this represents actual reversal in the regional trend or results from error in calculation and measurement is uncertain.

LITHOLOGIC CHARACTER

Sudair lithology is dominantly brick-red and green shale with subordinate red siltstone, sandstone and gypsum. Several thin lenses of carbonate are interbedded in the extreme northern and southern parts of the outcrop.

The type Sudair section, composited from several measurements at Al 'Arid, is the most complete sequence available (fig. 3). The upper part of the formation (65.8 m) was measured by R. D. Gierhart and L. D. Owens in 1948; the remainder, by Gierhart and R. A. Bramkamp in 1950. Their description of the Sudair is given in section 12 (p. 117).

Because of poor exposures, the Sudair north of the type locality has not been described in detail. Partial measurements and limited field observations do suggest, however, that the lithology of the formation is remarkably uniform. In most areas, dark-brick-red shale predominates. Siltstone, sandstone, and gypsum occur in all sections, but substantial amounts are present only in the north.

D. A. Holm, A. F. Pocock, and L. F. Ramirez in 1948 pieced together numerous poor exposures south of Wadi ar Rimah. The composite measurement gives some idea of lower Sudair rock types in this area. A white to tan, friable, poorly sorted, silty, and very fine to medium-grained sandstone directly overlies the Khuff. Weathered outcrops of this unit are often permeated with a white, gypsiferous powder, and slabs of satin spar litter the scree surface. Erosion commonly cuts the sandstone into a complex of narrow gullies and sharp, low-relief hills reminiscent of badlands

topography. Dark-brick-red gypsiferous shale is the main component above the basal sandstone. Some gray-green shale is present, and three thin, isolated beds of light-gray, finely crystalline dolomite (with some evaporite laminations) are included within the brick-red sequence. N. M. Layne, Jr., and H. L. McAlister in 1957 studied several short intervals of Sudair in the same general area. Beds of massive gypsum from 8 to 13 m thick were observed within the succession of red and purple gypsiferous shale.

Outcrops north of Buraydah were investigated by A. F. Pocock and R. P. Kopp in 1949. A combination of measured sections and calculated intervals indicates a thickness of 198 m of Sudair in this area. Most exposures are gray, rarely yellow, red, and green, friable, in part crossbedded, moderately sorted, fine- to medium-grained sandstone with common thin interbeds of red and gray-green shale and gypsiferous siltstone. Several thick beds of red and green shale and thin beds of red, impure limestone are present in the middle part of the formation.

NATURE OF CONTACT WITH ADJACENT FORMATIONS

Surface relationships, supported by subsurface data, indicate that the Sudair Shale conformably overlies the Khuff Formation along the entire length of outcrop. North of lat 22°00' N., the contact is usually shale on limestone. To the south, Sudair shale rests on sandstone.

Between lat 28°10' N. and 22°00' N. the Sudair is conformably overlain by the Jilh Formation (Middle Triassic). The contact is commonly marked by gradation upward from red and gray silty shale through ferruginous siltstone to mottled, fine-grained sandstone. Quaternary gravel masks events south of lat 22°00' N., but regional geometrical interpretation shows that the Jilh should be completely overlapped by Dhurma Formation (Middle Jurassic) in the vicinity of lat 21°00' N. At Khashm Kumdah (lat 20°17' N.) and in the northern part of Al 'Arid, Dhurma can be seen directly on Sudair.

Exposures in the face of the Al 'Arid escarpment show the unconformable Sudair-Dhurma contact rising uniformly to the south at a rate of 00°08' to 00°10'. At this rate, the Dhurma is cut out and the Sudair is intersected by the overlapping Tuwaiq Mountain Limestone (Upper Jurassic) just north of Khashm az Zifir (lat 19°30' N.). Continued pre-Tuwaiq Mountain truncation eliminates the Sudair a few kilometers south of Khashm Sudair.

PALaeONTOLOGY AND AGE

No fossils have been found in Sudair outcrops. Solely on the basis of stratigraphic position, the Sudair

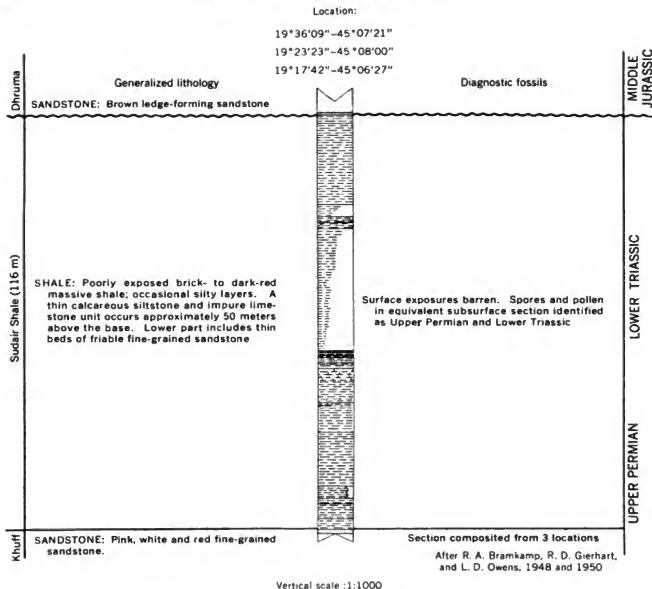


FIGURE 3.—Sudair Shale type section.

was originally presumed to be of Permian age (Steineke and Bramkamp, 1952b) and later, Permian or Triassic (Steineke and others, 1958).

Recent examination of Sudair floras recovered from wells has yielded new evidence indicating a Permian-Triassic contact within the formation. In wells where the lower Sudair is fossiliferous, an Upper Permian (Thuringian) flora is found. (D. O. Hemer, Aramco, unpub. data, 1962). Such bisaccate pollen as *Hoffmeisterites microdens* Wilson and various forms of *Lueckisporites* have been identified. The hystri-

sphaerid *Wilsonastrum*, closely associated with the Permian and Triassic contact, is also common.

Striated bisaccate pollen, so pronounced in the Jilh (Middle Triassic), also occurs in the upper part of the Sudair. The range of these bisaccate pollen grains begins immediately above rocks that contain Upper Permian pollen. As there is little variation in the Jilh and Sudair forms, the contact between Middle and Lower Triassic cannot be definitely determined. However, the development of striated bisaccate pollen is so closely related to the Early Triassic that there is

little doubt that the upper Sudair is assignable to this epoch.

ECONOMIC ASPECTS

GROUND WATER

For all practical purposes, the ground-water potential of the Sudair Shale is unknown. A number of shallow, hand-dug wells do exist in the Sudair outcrop belt, but nothing is known of their quality, productivity, or actual water source.

TRIASSIC SYSTEM

JILH FORMATION—MIDDLE AND UPPER(?) TRIASSIC

DEFINITION

The Jilh Formation is named for Jilh al 'Ishār, a low escarpment across which the type section was measured. Beds now assigned to the Jilh were first described by Max Steineke in 1937 (unpub. data) but were then included as part of a much larger sequence—the Es Sirr Member. At that time the Es Sirr and Khuff Members combined formed the Mustawi Formation. Later, in 1945, R. A. Bramkamp raised the Es Sirr and Khuff to formalational status, separated the Jilh limestone from bracketing strata, and designated the Jilh the middle of three members within the Es Sirr. From top to bottom the three members were: (1) Upper Es Sirr Sandstone (now Minjur Sandstone), (2) Jilh Limestone (now Jilh Formation), and (3) Lower Es Sirr Member (now Sudair Shale). Concurrently, Mustawi was raised to group rank. In 1951 R. D. Gierhart and Bramkamp changed the three Es Sirr Members to formations and, at that point, allowed the terms Es Sirr and Mustawi to lapse.

A list of the Permian and Triassic formational names now in use was published by Steineke and Bramkamp (1952b). Formal publication of Jilh and other type section particulars followed in 1958 (Steineke and others). The type Jilh section was measured and described on a nearly straight-line traverse from lat 24°03'48" N., long 45°46'00" E., northeast to lat 24°11'06" N., long 45°51'30" E.

The base of the formation is covered at the type locality, but the contact can be seen 3 km northwest where friable sandstone and green shale of the Jilh rests conformably on red shale of the Sudair. The top is at the contact between yellow-brown, slabby-weathering, fine-grained limestone below and tan, massive, commonly crossbedded sandstone of the overlying Minjur.

OCCURRENCE AND THICKNESS

Outcrops of the Jilh Formation form a narrow, arcuate band from Al Haddār (lat 22°00' N.) to the northern edge of Shāmat al Akbād (lat 28°10' N.), a distance of about 770 km. For all practical purposes

the Jilh is exposed continuously between Wādī Birk (lat 22°15' N.) and 'Irq al Maḥḥūr (lat 26°20' N.). To the north and south however, surficial deposits cover all but a few, thin, isolated patches. Throughout most of its outcrop, width of the Jilh ranges from 8 to 20 km.

The Jilh landscape, for some 70 to 80 km north of Wādī Birk, is dominated by a pair of steep, west-facing scarps. Near lat 24°00' N. these scarps break down and merge imperceptibly into a broad belt of low, multiple benches with a persistent regional strike of N. 29° W. This series of ragged, sand-drifted benches persists north to the Riyadh-Jiddah road and then gradually rises to a bold scarp whose steplike outer profile reaches a relief of 100 m at Ad Duwayhirah (lat 26°13' N.). The scarp continues north in bold relief until breached by the wide sand-filled channel of Wādī ar Rimah. North of the wādī, it becomes progressively less precipitous and all but loses its topographic identity before passing under sands of 'Irq al Maḥḥūr. Jilh rocks can be picked up within the 'Irq where they appear as low benches of slumped oolite in a broad sand-free area—Shāmat al Akbād.

Regional change in thickness of the Jilh is fairly well established by sections uniformly spaced along the outcrop. From the 26th parallel north there is little variation from an average thickness of about 240 m. The formation gradually thickens southward to a maximum of 326 m at the type section (near lat 24°00' N.). About 35 m of thinning occurs between the type locality and a section measured north of Wādī Birk. South of the wādī, the Jilh thins abruptly, and at the southernmost outcrop near Al Haddār, calculations show only 130 m of strata sandwiched between the Sudair Shale and Minjur Sandstone.

LITHOLOGIC CHARACTER

A characteristic feature of the Jilh Formation is marked vertical and lateral change in lithology. The picture is further complicated by the fact that softer units are often obscured by blocky talus derived from limestones capping individual benches. This is particularly true in the central area where differential relief between individual benches is seldom more than a few meters and the absence of crosscutting channels makes it difficult to get a true idea of the rock sequence.

At the type locality, near lat 24°00' N., the Jilh is chiefly a sandstone and shale unit with prominently exposed, but nonetheless subordinate, limestone. Concentration of the carbonate beds at the top and just below the middle of the section do help to subdivide the Jilh into smaller, more natural units (pl. 5).

South of the type locality the formation grades rapidly to sandstone. The isolated outcrop at lat 22°05' N. is the last one in which the Jilh can be sep-

arated with some certainty from the overlying sandstone of the Minjur.

Proportions of shale, sandstone, and limestone remain relatively constant from the type section north to Ad Duwaybirah, although some increase in calcareous content is evident. The succession does not, however, fall into any rough grouping similar to the type section, as various rock types are intimately interbedded throughout.

Significant change in Jilh lithology takes place north of Wādī ar Rimah as shale and sandstone in the lower two-thirds of the formation are progressively replaced by limestone. In connection with this, the sequence near the north end of Safrā' al Asyāb appears to be mostly carbonate. Of particular interest are thick gypsum beds found in the upper one-third of the unit near 'Ayn Ibn Fuhayd (lat 26°46' N.). Beds of gypsum as much as 13 m thick are intercalated with rubbly marl and shale through an interval of 70 m. Lack of exposures does not permit tracing of the gypsum to the northwest; however, the fact that the interval is occupied by a string of silt flats is, in itself, suggestive that evaporites and/or other soft beds do extend along the northeastern edge of Safrā' al Asyāb.

There is little doubt that Jilh deposits are, for the most part, continental, with limestones representing individual marine incursions. The general pattern indicates that the succession becomes increasingly calcareous and more marine to the north. This gradation is exaggerated by the surficial appearance of the outcrop itself. Black iron staining tends to emphasize the sandstone in the south at the expense of other rock components. Conversely, sandstone from Wādī ar Rimah north seldom weathers dark, and this, coupled with the blocky limestone talus from numerous low-relief benches, accents the carbonate content.

A section measured across the Jilh al 'Ishār by Max Steineke and others in 1945 was, later the same year, selected by R. A. Bramkamp to serve as the type Jilh. As this sequence (pl. 5) remains the most complete and best description of the Jilh Formation available, a detailed description is given in section 13 (p. 118).

In 1949, Bramkamp and S. B. Henry traversed the Jilh Formation west of Khashm al Manjūr (lat 23° 31' N.). Their work, coupled with limited reconnaissance mapping south of Wādī Birk, shows that south of the type locality the Jilh is mainly in sandstone facies. A summary of their description is given in section 14 (p. 119).

The cleanest exposures of the Jilh Formation, other than at the type locality, occur in Al Qasim (near lat 26°15' N.) and Safrā' al Asyāb. Rock types exposed in the Qasim closely resemble those at the type section. On the other hand, a distinctive facies shift to increased

carbonate can be seen along Safrā' al Asyāb. A measurement and description of the Al Qasim sequence was made near Ad Duwaybirah by A. F. Pocock and R. P. Kopp in 1949. The same year, they also compiled other representative Jilh sections near 'Ayn Ibn Fuhayd and Qidah (lat 27°06' N.). Generalized descriptions for these measurements are given consecutively in sections 15, 16, and 17 (p. 119-120).

NATURE OF CONTACT WITH ADJACENT FORMATION

Surface-subsurface relationships show the Jilh Formation to be conformable with Sudair Shale below and Minjur Sandstone above. Uppermost Sudair is visible on outcrop at only a few localities, and, as a consequence, the base of the Jilh is commonly taken at the lowest Jilh limestone bed. In this case, the contact falls within a gradational zone of sandstone, shale, and a few thin layers of red marly limestone. As the zone usually does not exceed 15 m in thickness, the accuracy of the pick probably varies no more than a few meters from the precise contact.

The upper Jilh contact is most often marked by a strong topographic break between sandy, commonly oolitic, cliff-forming limestone (Jilh) and medium- to coarse-grained, plains-forming sandstone (Minjur). In some areas, a thin, poorly exposed interval of platy marl, gypsiferous shale, and gypsiferous siltstone is sandwiched between the uppermost Jilh bench and the coarse sandstone of the Minjur.

The Jilh is the lowest of a series of formations that thin to the south and transgressively overlap each other onto the Sudair Shale. This transgressive relationship can still be seen in beds well up in the Jurassic. The decrease in Jilh thickness may be due to thinning against the margins of the basin, truncation by succeeding strata, or a combination of both. The absence of obvious unconformity adjacent to or within the Jilh is puzzling; however, conditions of deposition near the shield were remarkably constant, so that breaks within the stratigraphic section would be difficult to detect.

FALSBOTHOLOGY AND AGE

Fossils collected from Jilh exposures, mostly poorly preserved, include *Cardinia*?, *Myophoria* spp., *Pseudomonotis* sp., fragments and nuclei of ammonites, a few amphibian(?) bone fragments, and indeterminate pelecypods. Fossil wood has been observed at several levels, but the material has not been positively identified.

About 40 fragments and nuclei of ammonites (collected between 45 and 55 m below the top of the Jilh and near the Marāḥ-Buraydah road) were referred by Arkell (1952) to the *Paracerasites* fauna of Middle Triassic age. The same specimens were later examined in 1961 by N. J. Silberling (written commun.); he recognized most of them as clonitids and clydonitids

and their age as Late Triassic. Silberling states his "best guess as to a more refined stratigraphic assignment is Norian (upper Upper Triassic) based on the resemblance of some of the fragments to such genera as *Cylindrites*, *Sandlingites*, *Steinmannites*, and *Alloclonites*. However, assignment to an older part of the Upper Triassic is not precluded."

Other evidence on the age of the Jilh comes from bore holes where spores and pollens have been recovered from equivalent strata. The flora of the upper part of the Jilh contains such forms as *Cuneatisporites radialis* Leschik, *Pitysporites neomundanus* Leschik, *Uratetisporites mohri*, Leschik, *Ellipsosvelatisporites plicatus* Klaus, *Ovalipollis tunzensis* Klaus, *Enzonalsporites* sp., *Chordasporites sinlichorda* Klaus, and *Taeniaesporites* sp. In the lower part of the Jilh striated bisaccate pollen grains become dominant and include *Striatites jacobii* Jansonius, *Striatites richieri* (Klaus) Jansonius, *Platysaccus* sp., *Veryhacium* sp., *Luackisporites* spp., and *Taeniaesporites interruptus* Jansonius. According to D. O. Hemer, Aramco, (written commun., February 10, 1963), the bisaccate pollens found in the Jilh equivalent in bore holes have been published ranges from middle Keuper through Early Triassic (Scythian). Logical interpretation places the varied flora in the Middle Triassic.

Although the Jilh is considered here to be Middle Triassic, it is possible that at least part of the unit is Upper Triassic.

ECONOMIC ASPECTS

GROUND WATER

Aside from a few scattered shallow, hand-dug wells there has been no development of Jilh ground water.

MINJUR SANDSTONE—UPPER TRIASSIC

DEFINITION

The Minjur Sandstone is named for Khashm al Manjur (lat 23°31' N.) where the upper part of the formation is exposed. Max Steineke (unpub. data, 1937) did not originally set the Minjur apart from other Triassic units but included it, along with beds now assigned to the Jilh and Sudair, in the Es Sirr Member (obsolete). Subsequent subdivision of the Es Sirr and evolution of Triassic nomenclature is described in detail under the definition of the Jilh Formation (p. 35).

The type section of the Minjur extends from the eastern edge of the dip slope formed by the top bed of the Jilh Formation (lat 23°34'33" N., long 46°07'15" E.) up to the base of the Marrat Formation in the face of Khashm al Khalṣā' (lat 23°35'24" N., long 46°10'36" E.).

The base of the Minjur is at the contact between brown, sandy, oolite calcarenite with marine fossils

below (Jilh) and tan, commonly crossbedded, non-marine sandstone above. The upper limit is the unconformable contact of this sandstone with red shale of the Marrat.

OCCURRENCE AND THICKNESS

Outcrops of Minjur Sandstone have been identified over a distance of 820 km; that is, between lat 21°32' N. and 28°07' N. The southernmost occurrence is an isolated patch in front of the Tuwayq escarpment near Al Jil'an (lat 21°30' N.). From Al Haddār (lat 22°00' N.) north to 'Irq al Mazhūr (lat 27°14' N.) the Minjur is continuously exposed except for breaks at Wādī Birk and Wādī ar Rimah. Minjur rocks again appear in an outlier north of 'Irq al Mazhūr between lat 27°56' N. and 28°07' N.

The Minjur outcrop measures some 33 km across at its widest point near lat 24°30' N. Narrowing to the north and south, the last complete sections are less than 10 km wide.

North of the latitude of Khashm adh Dhibī (lat 24°13' N.) the Minjur typically weathers to a broad gravel plain with scattered black hills and low discontinuous benches. Relief is somewhat more pronounced toward the northern end of Safrā' al Mustawī where Jibāl Ar Rukhmān (lat 26°15' N.; long 44°29' E.) and Burmah (lat 26°19' N., long 44°27' E.) rise 30 m above the surrounding gravel-covered surface. Wādī ar Rimah marks the northern limit of the Safrā' al Mustawī plain, and beyond, the Minjur forms a broad trough filled with silt flats. From Khashm adh Dhibī south the band of Minjur narrows; the upper part is exposed in a steep slope at the foot of Jabal Tuwayq, and the lower part mostly obscured by gravel cover.

The Minjur Formation is 315 m thick at Khashm al Khalṣā', the type locality. There is little change in thickness as far south as Khashm Māwān (lat 22°50' N.) where 326 m were measured. South of Khashm Māwān some thinning is apparent, presumably owing to truncation and overlap by Lower and Middle Jurassic units. Thicknesses and relationships in this area are obscured, however, because of strong lithologic similarity of Minjur with bracketing strata.

The Minjur Formation shows definite thinning north of the type locality. About 290 m of section was measured at Khashm adh Dhibī, 195 m was measured and computed near Ar Rukhmān and 185 m was calculated north of Wādī ar Rimah.

LITHOLOGIC CHARACTER

The Minjur Formation is essentially a littoral-continental sandstone with small amounts of conglomerate and shale. The lithologic character of the unit as a whole is remarkably persistent along strike.

It is typically a white to tan to brown, medium-grained, poorly sorted, crossbedded quartz sandstone that weathering commonly alters to jet-black quartzite masses. The sand is often friable, crushing readily in the hand. Lenses of conglomeratic sandstone occur at a number of levels, and some thin beds of red, purple, and green shale are intercalated. Ripple marks, mud cracks, and sandbar structures are common, and fossil dunes occur in the upper part of the section. No marine fossils have been found, but several forms of fossil plant material are present throughout. These include crude stem impressions and molds of limbs and trunks of trees as well as silicified wood.

The most detailed description and measurement of the Minjur is that made at Khashm al Khalat' in 1951 by R. A. Bramkamp and others (pl. 6). This section, now designated as the type Minjur, is given in section 18 (p. 120).

The lower and upper parts of a complete Minjur section (327 m) were measured in the face of Khashm Māwān (near lat 22°50' N.) respectively by R. D. Gierhart and L. D. Owens in 1947 and R. A. Bramkamp and H. A. Kimball in 1950. The lithology at this latitude, as well as in the localities studied further south, is mainly sandstone with subordinate shale. The sandstone is off-white to tan to brown, red and black weathering, generally crossbedded, medium to coarse grained, and commonly friable. The shale, occurring as thin interbeds throughout the sequence, is gray, purple and red, and commonly silty or sandy. Maximum thickness of any individual shale bed seldom exceeds 5 m. Several thick beds of quartz-pebble conglomerate occur, one at the top of the Minjur and others near the base.

Traverses north of the type locality also show little variation in lithology. A. F. Pocock and R. P. Kopp in 1949 pieced together a typical section from intervals measured and computed near lat 26°15' N. Most outcrops, through the 196-m succession, are light-colored, in part black-weathering, fine- to coarse-grained, poorly sorted, crossbedded sandstone. Thin beds of varicolored gypsiferous shale are scattered through the section, and two weak benches of thin-bedded, platy marl occur in the middle part of the formation.

In summary, Minjur lithology—both vertically and laterally—is a monotonous succession of light-colored, crossbedded sandstone with perhaps 10 percent shale occurring at various levels. Lenses of conglomeratic material are common.

NATURE OF CONTACT WITH ADJACENT FORMATIONS

The contact between the Minjur and underlying Jilh Formation is generally marked by a strong topographic

break from cliff-forming, sandy and oolitic limestone capping the Jilh to deeply weathered, crossbedded sandstone of the Minjur. There is commonly a very thin, poorly exposed gradational zone of platy-weathering marl and gypsiferous shale. This contact is conformable and can be traced with few interruptions throughout the length of outcrop.

The top of the Minjur represents an unconformity. From Khashm adh Dhibi north this contact is between maroon siltstone or gray to black-weathering sandstone of the Minjur and gray to tan, tight limestone of the basal Marrat. South of Khashm adh Dhibi the basal Marrat grades to shale, siltstone, and eventually sandstone near lat 23°00' N., where, because of lithologic similarity, the break can no longer be recognized with certainty. The Minjur south of lat 22°00' N. is obscured by cover; however, geometrical interpretation of bracketing units suggests that complete wedge-out occurs near lat 21°00' N. At least part, and probably most, of the cutting takes place at the top. In connection with this, Dhurma beds (Middle Jurassic) overlap the Marrat (Lower Jurassic) just south of Khashm Māwān, transgress the Minjur and Jilh, and butt against Sudair (Permian and Triassic) near Wādī ad Dawāsīr.

Obvious thinning of the Minjur can be seen between Khashm adh Dhibi and Wādī ar Rimah. There is no evidence to indicate whether pre-Marrat erosion or depositional thinning is involved. The last vestiges of the Minjur are beveled and disappear beneath the Wasia Formation (Middle Cretaceous) near the southern edge of At Taysiyah plateau (lat 28°05' N.).

PALEONTOLOGY AND AGE

Only fossil wood has been found in surface exposures of the Minjur Sandstone. On its basis of the stratigraphic position, Steineke and others (1958) considered the Minjur to be Upper Triassic or Lower Jurassic.

Palynological investigation of Minjur sediments recovered from deep bore holes has recently shed more definitive light on the age of these beds. The lower part of the Minjur contains a predominance of the pollen grains *Sulcatissporites interpositus* Leschik described from the middle Keuper of Switzerland and *Pityosporites rutneri* Klaus as described from the Carnian (or middle Keuper) of Austria. Directly above these forms, Minjur strata contain an entirely different monosaccate flora. These in turn are overlain sharply by a Lower Jurassic flora falling within the Marrat Formation dated by ammonites as Toarcian (Early-Jurassic). If the middle Keuper dating of the very small bisaccates is correct, it can be assumed the monosaccate flora represents a zone of late Keuper age. That they are Late Triassic is fairly certain. Using

these data, the Minjur can now be dated as Late Triassic with some confidence.

ECONOMIC ASPECTS GROUND WATER

In the vicinity of Riyadh several deep wells penetrate the Minjur Sandstone. These now produce large quantities of potable water from this aquifer. Elsewhere only a few hand-dug wells exist, and the ground-water potential is virtually unknown.

JURASSIC SYSTEM

MARRAT FORMATION—LOWER JURASSIC DEFINITION

The Marrat Formation takes its name from the town of Marāh (lat 25°04' N., long 45°29' E.) near where the type section was pieced together. Marrat strata were at first considered by Max Steineke to be the basal member of the Tuwaiq Formation. In 1945 the Marrat was raised to formational status by R. A. Bramkamp and Steineke, and, concurrently, the Tuwaiq was redesignated a group. The Tuwaiq Group included the Marrat, Dhurma, Tuwaiq Mountain, Hanifa, and Jubaila Formations. Formal publication of formational names followed (Steineke and Bramkamp, 1952b), and, at about the same time, usage of the term Tuwaiq Group was discontinued. Finally, Steineke and others in 1958 published particulars of the Marrat type section.

The lower part of the type section was measured in the escarpment (at lat 25°03'00" N., long 45°25'42" E.) about 5 km southwest of Marāh; the middle part, in Jabal Kumayt (lat 25°04'48" N., long 45°28'18" E.) immediately north of Marāh; and the upper beds, southeast of Marāh (near lat 25°01'30" N., long 45°33'00" E.).

At the type locality, the base of the Marrat Formation is at the contact between thin, bedded limestone above and gray, angular sandstone below. The top is at the change from Marrat gray (golden-brown-weathering) limestone to olive-green, occasionally gypsiferous shale of the overlying Dhurma.

OCCURRENCE AND THICKNESS

Discontinuous exposures of the Marrat Formation can be traced from Khashm Māwān (lat 22°50' N.) to the At Taysiyah plateau (lat 28°03' N.), a distance of more than 650 km. The outcrop band reaches its maximum width, about 15 km, in the vicinity of Marāh. From Khashm adh Dhibi (lat 24°13' N.) south, the formation narrows and loses topographic distinctiveness as it dips under the protective ledge of the Tuwayq escarpment. In the area immediately north of Khashm adh Dhibi, isolated remnants of

Marrat can be seen within and along the northern margin of Nafūd Qunayfihah. The erratic outcrop pattern is, at least in part, related to local fractures and flexures—splayed offshoots from the central Arabian graben system.

Marrat is again cleanly exposed north of the fault zone where two continuous, though low-relief, scarps are readily recognizable. The benches become progressively more prominent to the north and, in the vicinity of Marāh and Shaqrā' (lat 25°15' N.), form a pair of steep west-facing cuestas that dominate the landscape. The upper escarpment, 55 m in height, is formed by erosion of soft red shale under a resistant cap of upper Marrat limestone. The lower scarp, 40 m high, is held up by rough, blocky-weathering, lower Marrat limestone.

North of Shaqrā', the escarpments gradually break down. The upper bench disappears under the sand of Nafūd ath Thuwayrāt near lat 25°27' N. and does not crop out again. The basal escarpment, progressively decreasing in height, persists to the northwest (along the Safra' al Mustawī), passes under a thin veneer of sand near lat 25°45' N., and emerges a short distance north as a low, intensely weathered bench of reddish-gray limestone—the Sharābith escarpment. Dunes of Nafūd ath Thuwayrāt again completely overlap the lower Marrat at lat 26°17' N. Further north, along strike, interdune hollows within the 'Irq al Mazhūr are floored with highly weathered basal Marrat limestone. Another outlier of this limestone, the most northerly occurrence of Marrat known, has been identified on the far side of the 'Irq near lat 28°00' N.

The Marrat Formation reaches a maximum thickness of 111 m near Marāh, the type locality. Uniform thinning occurs to the north and south. A section composited 15 km north of Shaqrā', near where the last complete Marrat sequence is exposed, showed the formation to be slightly less than 90 m thick. South of the type locality, sections measured at lat 24°13' N. (Khashm adh Dhibi), 23°57' N. (Khashm al Jufayr), 23°40' N., 23°31' N. (Khashm al Manjūr), and 23°12' N. (Wādī Birk) were respectively 102, 92, 70, 50, and 41 m thick. The gradual southward reduction in thickness defined by these measurements apparently continues beyond Wādī Birk, but here unit boundaries are uncertain.

LITHOLOGIC CHARACTER

In the northern area of exposure, where the Marrat was first studied, three natural topographic-lithologic subdivisions are readily visible. Basically the pattern is a soft red shale bracketed by resistant limestones. In spite of significant facies changes, the three members can be traced without difficulty south to Khashm al Jufayr.

The lower limestone member is typically exposed in the Sharābith escarpment west of Nafūd ath Thuwayrāt. South of Sharābith, the member crops out almost continuously to the Šafrā' al Mirakah (lat 24°36' N.) disappears under Nafūd Qunayfidlah, reappears at Khashm Dhuwaybān, and is again exposed below the Dhibi escarpment from Khashm adh Dhibi south to Khashm Māwān. Mostly limestone in the north, the lower part of the member is mainly sandstone and shale at Khashm Dhuwaybān (24°28' N.). The upper part of the member grades to clastics just south of Khashm al Jufayr.

The Marrat red shale member is thickest between Shaqrā' and Khashm adh Dhibi. Northwest of Shaqrā', sandstone and conglomerate displace shale before the sequence passes under Nafūd ath Thuwayrāt (lat 25°27' N.). South of Khashm adh Dhibi, the red shale member maintains lithologic identity to Khashm al Jufayr though a thick wedge of red, silty sandstone appears in the upper part. Beyond this point, progressively more sandstone is added at the expense of shale.

The upper Marrat limestone, which caps a strong escarpment, can be traced with few interruptions from Nafūd ath Thuwayrāt to Khashm Qarādān (lat 24°45' N.). The limestone again crops out in the face of Khashm adh Dhibi. South of Khashm adh Dhibi, limestone is gradually replaced from the bottom up by shale until, at Wādī Birk, there remains only a thin limestone bed capping the sequence. Significant amounts of sandstone also occur here, and immediately south of the wādī, sandstone replacement is complete.

The "typical" Marrat is best illustrated by the reference sequence measured in front of Khashm adh Dhibi. Changes to the north and south are demonstrated by other selected sections.

In 1962, Powers and McClure sampled in detail a complete Marrat sequence in the face of Khashm adh Dhibi (along lat 24°13' N.). Samples collected at 1-m intervals were later cut, polished, and described according to the Aramco carbonate rock classification (Bramkamp and Powers, 1958; Powers, 1962). Since this measurement affords the most complete data on the Marrat, it has been designated a reference section (fig. 4). The section was measured in two increments: (1) Lower 21.5 m in front of Khashm adh Dhibi from lat 24°13'11" N., long 46°05'53" E., to lat 24°13'06" N., long 46°05'58" E., and (2) upper 81.0 m in the face of the Dhibi escarpment from lat 24°13'15" N., long 46°06'20" E. to lat 24°13'20" N., long 46°06'41" E.. The Marrat reference sequence is given in section 19 (p. 121).

Several complete traverses and measurements of the Marrat have been made south of the reference section.

One such measurement, by Max Steineko and others in 1945 in the vicinity of Khashm al Jufayr (lat 23°57' N.), shows gradual introduction of shale at the expense of limestone and sandstone at the expense of shale. The sequence is summarized in section 20 (p. 122).

Still further south, R. A. Bramkamp and others in 1945 measured the Marrat at Khashm al Manjūr. At this point substantial changes in lithology can be observed; most of the section is sandstone and shale, only a vestige of the basal limestone is present, and the lower and middle Marrat can no longer be separated. The sequence is summarized in section 21 (p. 122).

Definite Marrat is identifiable as far south as Khashm Māwān. The upper formation boundary cannot, however, be placed with certainty, as the contact involves sandstone on sandstone. Bramkamp and H. A. Kimball described the entire Māwān sequence in 1950 and assigned about 37 m to the Marrat. A summary of their notes is given in section 22 (p. 122).

The Marāh area affords the best exposures of the Marrat Formation northwest of the reference section. It was there, in fact, that the type Marrat was pieced together. The whole sequence does not crop out at a single locality but must be composited from several sections generally along lat 25°02' N. There, the three informal members of the Marrat are typically developed. The lower and middle members were described by D. A. Holm and A. F. Pocock in 1948; the upper, by Bramkamp and others in 1949. The succession is summarized in section 23 (p. 122).

A partial section, covering the middle red-shale member, was measured north of Shaqrā' (near lat 25°20' N.) by Holm and Pocock in 1948. At this latitude the middle unit has thinned to 37.3 m, the upper one-half is in massive, buff to red, crossbedded sandstone facies, and the lower part is maroon, in part sandy, shale. A short distance north, recent sand blankets the middle and upper Marrat, but outcrops of the lower limestone persist along strike. Pocock and R. P. Kopp in 1949 calculated a thickness of 39 m for the lower member near lat 26°10' N. Sporadic exposures at this latitude suggest the sequence is mainly brown to gray, tight, aphanitic limestone. Outcrops of lower Marrat, still in carbonate facies, have been traversed further north, but detailed data on these outliers is lacking.

NATURE OF CONTACT WITH ADJACENT FORMATIONS

Regional beveling of underlying strata and absence of lower and middle Liassic stages show the lower Marrat contact to be unconformable. In the northern area of outcrop, the boundary between Marrat and Minjur is placed at the contact of tan and brown lime-



FIGURE 4.—Marrat Formation reference section.

stone above and gray, friable, crossbedded sandstone below. Most commonly, the basal Marrat forms a massive ledge from which large blocks of limestone talus slide down over a steep Minjur slope. From Khashm adh Dhuwaybān to Khashm al Manjūr a 1-m thick bed of tan limestone or dolomite marks the basal Marrat. Usually, however, the bed is covered by scree, and the contact is identified by a change from cross-bedded sandstone below to olive-green shale above. Continuous tracing of beds has established the contact as far south as Khashm Māwān although, at this point, sandstone rests on sandstone. The lower Marrat limit cannot be set farther south.

The Marrat contact with the overlying Dhurma Formation is conformable throughout most of the length

of outcrop. A marked topographic break accompanies the lithologic change. Cliff-forming aphanitic limestone (Marrat) is sharply overlain by soft, olive-green shale or, more rarely, gypsum (Dhurma). The picture changes in the vicinity of Wādī Birk where the upper Marrat limestone and lower Dhurma shale are, in large part, replaced by sandstone. South of Wādī Birk the two formations can no longer be separated on lithologic or topographic grounds. As an added complication, it is likely that Dhurma overlap comes into play in this area. In fact, the Marrat is completely pinched out not far south of Khashm Māwān, and Dhurma beds transgress onto Minjur.

So far as the northern limit of Marrat is concerned, mapping shows the formation truncated by Wasia

(Middle Cretaceous) sandstone just beyond lat 28°00' N.

PALEONTOLOGY AND AGE

The Marrat Formation has been dated confidently as Toarcian by ammonites (Arkell, 1952). *Nejdia bramkampii* Arkell and *Hildaites sanderi* Arkell were collected from the upper member, the middle member is barren, and lower Marrat beds have yielded *Bouleiceras nitescens* Thevenin, *B. elegans* Arkell, *B. arabicum* Arkell, *B. marraticum* Arkell, and *Protogrammoceras madagascariense* Thevenin. The *Bouleiceras* fauna is considered by Arkell to be lower Toarcian; the *Nejdia* fauna is dated by him as early upper Toarcian.

Palynological determinations (D. O. Hemer, unpub. data, 1963) of surface samples obtained by air drilling indicate that the Marrat-Minjur contact also marks the Jurassic-Triassic boundary. The Lower Jurassic flora consists primarily of the form *Classopollis* and associated trilete spores. Marine microflora are rare, although a small number of dinoflagellates and hystriophospherids are present. Abundant Upper Triassic monosaccate pollen grains immediately underlie this flora.

These data, taken collectively, indicate that early and middle Liassic time is not represented on outcrop.

A rather impressive and varied collection of megafossils was made during early field work, particularly in the vicinity of Khashm adh Dhibi. These brought about the early recognition of a Liassic (Early Jurassic) age for the Marrat, a determination refined by the later work of Arkell. A complete list of identified fossils includes: "*Rhynchonella*" sp., *Spiriferina* spp., "*Terebratula*" spp., *Anabacia* sp., *Montivallia* sp., *Acrostenia* cf. *A. somaliensis* Currie, *Hemipetina*? spp., *Bouleiceras nitescens* Thevenin, *B. arabicum* Arkell, *B. marraticum* Arkell, *B. elegans* Arkell, *Hildaites sanderi* Arkell, *Nejdia bramkampii* Arkell, *Nejdia furnishi* Arkell, *Protogrammoceras madagascariense* Thevenin, *Ampulicella* sp., *Cardium* (s.l.) sp., *Ceratomya* spp., *Ceratomya*? sp., *Ceromyopsis arabica* Cox, *Chlamys* sp., *Discoelz* sp., *Eligmus* sp., *Globularia* cf. *G. hemisphaerica* Roemer, *Gryphaea* sp., *Jibula*? sp., *Lima* cf. *L. gigantea* (Sowerby), *Lima* cf. *L. harroni* Dacque, *Loph* sp., *Modiolus* (*Inoperna*) sp., *Mya* sp., *Mytilus* (*Arcomytilus*) sp., *Mytilus*, *Arcomytilus somaliensis* Cox, *Mytilus*? sp., *Nautilus* sp., *Nerinea* sp., *Nerita*? sp., *Ostrea* spp., *Oryzoma* sp., *Pholadomya* spp., *Pholadomya* (*Homomya*) inornata Sowerby, *Pholadomya lirata* (Sowerby), *Pleuromya*? sp., *Protocardium* sp., *Pseudotrapezium*? sp., *Pseudomelania* sp., *Pteria* (s.l.) *Purpuroides*? sp., *Quenstedtia* sp., *Thracia* sp., *Turbin*? sp., *Turbo* (s.l.); indeterminate lucionids, nautiloids, indeterminate molluscs, ostracodes.

ECONOMIC ASPECTS

GROUND WATER

In the vicinity of Shaqrā', deep water wells are currently producing from the Minjur Sandstone. The holes are probably open to the Marrat as well; however, the quantity of water, if any, being withdrawn from this unit is unknown. No other data on Marrat water potential is available.

DHURMA FORMATION—MIDDLE JURASSIC

DEFINITION

The Dhurma Formation is named for the town of Dūrmā (lat 24°36' N.; long 46°07' E.) near the middle of the outcrop belt. Max Steineke in 1937 first defined the Dhurma as a member of the Tuwaiq Formation along with the Marrat, Tuwaiq Mountain, Hanifa, Jubaila, Arab, and Hith members. In 1945, R. A. Bramkamp raised each member to formation and raised the Tuwaiq to group. Formal publication of formation names followed (Steineke and Bramkamp, 1952b), and, concurrently, the term Tuwaiq Group was dropped. Type section particulars were published by Steineke, Bramkamp, and Sander (1958).

The type sequence was composited from a series of successive measurements at Khashm adh Dhibi (lat 24°12'24" N.; long 46°07'30" E.) and between Khashm adh Dhibi and Khashin al Mazrū' (lat 24°19'00" N.; long 46°19'36" E.). This succession in the face and on the back slopes of Khashm adh Dhibi is one of the most accessible and best exposed.

At the type section, the base of the formation is at the contact between the gypsum and interbedded shale and limestone and the underlying cliff-forming Marrat limestone; the top is placed at the contact between olive-green shale of the upper Dhurma and light-brown, soft, chalky limestone of the Tuwaiq Mountain Limestone.

The major subdivisions of the Dhurma Formation defined by Steineke, Bramkamp, and Sander (1958) are retained in this report. These are (1) upper Dhurma—here divided into two members, (2) middle Dhurma—containing the ammonite zones *Dhurmaites*, *Micromphalites*, *Tuaites*, and *Thambites*, and (3) lower Dhurma—with the *Ermoceras* zone at top, two unnamed units in the middle, and the *Dorsetenia* zone at the base (pl. 7).

The upper Dhurma is divided on lithologic and faunal evidence into two distinct members—the Hisyān above and the 'Atash below. The definition of these members is published here for the first time.

The Hisyān Member is named for Wādī al Hisyān (near lat 24°50' N.), a major drainage channel that cuts directly across the unit. Holm, who first proposed

the member in 1947, did not designate a type locality, although it is known that some beds he placed at the top of this unit are not now included within it.

Type locality for the Hisyān Member is designated as Khashm al 'Atāsh (lat 24°10'50" N., long 46°27'53" E.) where the complete section (46.5 m) is cleanly exposed. The upper limit is at the lithologic change from shale with thin interbeds of limestone below to limestone with thinly interbedded shale above. Lithologically, the upper contact is somewhat gradational; faunally, it is sharp. The lower limit of the member is firmly fixed at the break from yellow-gray shale above to yellow-brown calcarenite of the 'Atash Member below.

The 'Atash Member is named for Khashm al 'Atāsh (lat 24°10'50" N., long 46°27'53" E.) where the upper 14.1 m is cleanly exposed. The lower 12.2 m was described from samples from a shallow air-drilled hole, T-80, spudded in at the base of the section used to define the upper 'Atash. The lower limit of the member is at the change from chalky calcarenitic limestone above to impure calcarenitic limestone and calcarenite of the *Dhurma* zone below.

Considerable economic importance is attached to the 'Atash Member as it is equivalent, both lithologically and faunally, to the subsurface Fadhlī reservoir—an important oil-bearing interval in eastern Arabia.

OCCURRENCE AND THICKNESS

Beds of the *Dhurma* Formation form a boomerang-shaped arc extending from Al 'Arid (near lat 19°20' N.) to 'Iraq al Mazhūr (near lat 27°05' N.), a distance of more than 900 km. The outcrop belt reaches a maximum width of 20 to 25 km in the vicinity of Wādī Birk-Khashm adh Dhibī and narrows irregularly to the north and south.

Dhurma topography in the vicinity of Khashm adh Dhibī is dominated by three prominent limestone benches. The lowermost of these is capped by the Dhibī limestone which supports the high outer escarpment of Jabal Tuwayq. Just north of Khashm adh Dhibī, the central Arabian graben system breaks the topographic continuity of the scarps, but beyond, the benches can again be accurately identified.

Dhurma outcrops north of the grabens are generally poor exposures of intensely weathered shale under capping ledges of limestone or, more rarely, sandstone. Many interbench areas are floored with long broken ribbons of yellow silt. While this makes detailed lithologic description difficult, it has a decided advantage so far as precise segregation of fossil horizons is concerned. The benches become progressively more subdued until they are covered near Al Qasab (lat 25°18' N.) with a flood of silt and gravel from the

mouth of Wādī al 'Atk. North of the wadi only a single bench, probably the middle one, remains as a traceable topographic feature, and the *Dhurma* forms a lowland of banded mud flats and low benches sandwiched between the Tuwaiq Mountain Limestone escarpment and the Nafūd ath Thuwayrāt. The Nafūd effectively covers the lower part of the formation throughout most of the area; middle and upper beds are commonly disrupted and blanketed by a flood of outwash from the Tuwayq front.

From Al Furthī (lat 25°40' N.) to Az Zilfī (lat 26°18' N.), the *Dhurma* appears only in a few gravel-strewn windows in surficial deposits. The formation is completely overlapped by sands of Nafūd ath Thuwayrāt about 20 km north of Az Zilfī. Small patches reappear near lat 27°00' N. as yellow silt flats and sandy-marly benches in hollows within the 'Iraq al Mazhūr.

From Khashm adh Dhibī south, the *Dhurma* is remarkably well exposed in a step-like series of high, limestone-capped scarps and broad dip slopes. Of the three benches identified by Holm, only the lower or Dhibī bench has been traced south, and it can be recognized with certainty at Al Haddār (lat 22°00' N.). Immediately south of Al Haddār, *Dhurma* limestone is largely replaced by shale and sandstone. As a consequence massive scarps fade, and the *Dhurma* retreats under a protective cap of Tuwaiq Mountain Limestone.

Maximum thickness of the *Dhurma* Formation is at the Khashm adh Dhibī reference section where 375 m was recorded. Southward the formation thins uniformly to 264 m at Wādī Birk and about 200 m at Khashm al Juwayfah (lat 22°32' N.). Thicknesses are uncertain beyond this point, as lower *Dhurma* sandstone is indistinguishable from sandstone of the underlying Marrat, Minjur, and Jilh Formations. The general picture, however, is one of continued southward thinning through progressive loss of beds at the base by overlap. Finally the *Dhurma* wedges out against the Sudair Shale near Khashm az Zilfī (lat 19°30' N.).

The few *Dhurma* sections available north of the reference locality indicate less drastic thinning in this direction. Intervals measured and computed near lat 25°02' N., 25°32' N., and 26°02' N., and calculated across the 'Iraq al Mazhūr give thicknesses of about 375, 350, 330, and 250 m respectively.

LITHOLOGIC CHARACTER

In the area between Wādī al Hawtah (lat 23°33' N.) and Ar Raghbah (lat 25°09' N.), the upper and lower benches mapped by D. A. Holm in 1947 separate the *Dhurma* into three natural units corresponding to the upper, middle, and lower *Dhurma* as defined by Steineke, Bramkamp, and Sander (1958) and as used in this re-

port. Basically, the pattern from bottom to top is: (1) lower Dhurma—shale with some limestone that near Khashm adh Dhibi contains a thin layer of gypsum at the base and that has an upper bed of massive, cliff-forming Dhibi limestone, (2) middle Dhurma—limestone containing beds of clean, current-washed calcarenite at various levels, many as units with high-lateral persistence, and an upper oolite bed that forms a prominent cliff, and (3) upper Dhurma—shale (Hisyan Member), with some limestone in lower part ('Atash Member).

The most important lateral change in the Dhurma Formation is the southward replacement of limestone and shale by sandstone. The first change is in the lower Dhurma which becomes dominantly sandstone in the vicinity of Khashm al Khalṭā' (lat 23°36' N.); the middle and upper members give way to sandstone near Al Haddār (lat 22°00' N.). Change from limestone to sandstone takes place abruptly in individual beds, usually without passing through a shaly phase. The southward change in facies represents transition from marine to continental deposition.

In the north beyond Ar Raghbah the proportion of shale in the Dhurma gradually increases until it dominates the sequence near Al Jurayfah (lat 25°31' N.). A few thin beds of sandstone also occur here; progressively more are added northward. Although the trend toward shoreline conditions is obvious, marine beds still make up a considerable part of the sequence just before the Dhurma passes under the Nafūd ath Thuwayrāt.

Selected sections give a more detailed picture of lateral lithologic changes in the Dhurma. The excellent exposures at Khashm adh Dhibi are characteristic of the sequence in the central area of outcrop. R. W. Powers and H. A. McClure measured this section in 1962 and prepared a detailed description of the lithologies from polished sections of samples collected at intervals of 1 m or less. The new measurement, pieced together in the same general area as the type section (Steinke, Bramkamp, and Sander, 1958), is herewith designated a reference section (pl. 7). A complete succession was composed from three increments—(1) the lower 120.8 m was measured in the face of the Dhibi escarpment between lat 24°11'17" N., long 46°11'10" E. and lat 24°11'53" N., long 46°11'30" E., (2) the middle 63.7 m on the back slope of the Dhibi limestone between lat 24°11'04" N., long 46°17'14" E. and lat 24°11'12" N., long 46°17'17" E., and (3) the upper 190.0 m in the face of the Tuwaīq Mountain Limestone scarp between lat 24°11'19" N., long 46°18'50" E. and lat 24°12'34" N., long 46°19'03" E. A full description is given in section 24 (p. 123).

South of the reference locality the lower Dhurma is

the first to undergo significant change. The Dhibi limestone persists but underlying beds show slight replacement by sandstone as far north as Al Jufayr (lat 24°01' N.). However, most of the replacement occurs between Farīdat Bal'ūm (lat 23°42' N.) and Khashm al Khalṭā' (lat 23°36' N.).

The next complete traverse of the Dhurma was made at Wādī Birk (lat 23°12' N.) where the lower part of the formation is mostly sandstone and upper units show little change from the reference section. In 1945, R. A. Bramkamp and C. W. Brown described the lower Dhurma; the middle and upper members were covered by R. D. Gierhart and P. R. Aswerus in 1947. The sequence is summarized in section 25 (p. 129).

Dhurma lithology at Khashm al Juwayfah (lat 22°32' N.) is similar to the Wādī Birk sequence but does exhibit some differences. Notable changes include: (1) an increase in shale at the expense of limestone, probably involving beds equivalent to the 'Atash Member, (2) introduction of considerable crossbedding and fossil wood in the lower sandstone, and (3) loss of definition of the Marrat-Dhurma contact, although bracketing markers permit approximate placement. Further south the contact is lost completely.

The Al Juwayfah section was pieced together from two isolated measurements. Gierhart and L. D. Owens described the lower Dhurma in the face of the Khashm in 1947; Bramkamp measured the middle and upper units opposite Khashm 'Ushayrah (lat 22°36' N.) in 1951. The section is summarized in section 26 (p. 130).

Sections at Khashm Kharṭam and along the northern edge of Sha'tb al Haddār (near lat 22°00' N.) show small but significant changes relative to the Al Juwayfah sequence described above. For example: (1) a thick lense of impure limestone and calcarenite has been introduced, presumably in the lower part of the Hisyan Member—in bracketing sections the interval is occupied by shale, (2) interbeds of sandstone occur near the probable level of the 'Atash Member, (3) the Dhibi limestone is present at both localities but has lost its cliff-forming character in the Haddār section, and just to the south it is replaced by sandstone, and (4) beds below the Dhibi are sandstone which cannot be distinguished from underlying Triassic units.

Major lithologic variations are evident about 5 km south of Al Haddār and at Khashm ash Shajari (lat 21°46' N.). South of Al Haddār, shale dominates the post-*Micromphalites* interval; remaining section exposed (only above the Dhibi) is limestone. At Khashm ash Shajari, sandstone is the main constituent, only the lower half of the *Micromphalites* zone being in carbonate facies. The two sequences are summarized in sections 27 and 28 (p. 130), respectively.

South of Khashm ash Shajari the Dhurma Formation is, with the exception of a several-meter-thick limestone at the base of the *Micromphalites* zone, made up of sandstone and minor shale interbeds. The above-mentioned limestone has been partly replaced by shale at Khashm Mishlah (lat 21°08' N.) and completely replaced by shale at Khashm Taryam (lat 20°37' N.); at Khashm Kumdah (lat 20°17' N.) the equivalent interval is entirely represented by sandstone. Southward from this point the Dhurma continues in sandstone facies, eventually wedging out between Tuwaiq Mountain Limestone and Sudair Shale near Khashm az Zifr (lat 19°30' N.).

North of the reference section the middle Dhurma is the first unit to show perceptible change. By the time Khashm al Haysiyah is reached (lat 24°51' N.) significant amounts of shale have been added at the expense of limestone. Essentially the same limestone-shale ratio is maintained in the better exposed outcrops in front of Khashm at Turab (lat 25°03' N.).

The closest possible approach to a complete Dhurma sequence (in the northern area) was composited from three individual sections measured approximately along lat 25°02' N. Here, D. A. Holm and A. F. Pocock described the upper Dhurma in 1948; R. A. Bramkamp and others described the middle and lower Dhurma in 1949. The sequence is summarized in section 29 (p. 131).

Progressive addition of shale to the north results in almost complete replacement of limestone in the vicinity of Al Jurayfah (lat 25°31' N.). An almost full succession, except for the basal part, can be pieced together from measurements of the upper Dhurma made by Bramkamp and others in 1951 and the middle and lower Dhurma by Pocock and R. P. Kopp in 1948. The sequence is summarized in section 30 (p. 131).

Dhurma exposures in the vicinity of Al Ghât (lat 26°02' N.), the northernmost area studied in detail, are poor but do suggest some significant shifts in facies. The 66.4 m of upper Dhurma, measured by S. J. Roach in 1952, is distinctly typical in that most of the Hisyan beds are greenish-gray, impure, nodular-weathering limestone in the upper part and reddish-brown, impure, sandy, fossiliferous, oolitic-detrital calcarenitic limestone in the middle. The probable equivalent of the lower Hisyan and 'Atash is olive-green, silty and sandy shale with rare thin interbeds of greenish-gray sandstone and coquinoid limestone.

The middle and lower Dhurma interval was examined by Pocock and Kopp in 1948. Brown, greenish-brown to black-weathering, medium, to coarse-grained, ripple-marked sandstone in beds 1 to 2 m thick crops out as ledges at 5, to 30-m intervals throughout the upper 156 m. Interbedded intervals are usually masked, but

some shale was discovered in the lower 40 m. An estimated 108 m of covered section intervenes between the last sandstone ledge and the projected top of the Marrat Formation. Therefore, the approximate total thickness of the Dhurma Formation near Al Ghât is 330 m. Essential details of Dhurma lithology are unknown to the north.

NATURE OF CONTACT WITH ADJACENT FORMATIONS

In the central area from Wâdi Birk to lat 25°00' N., the Dhurma contact with the underlying Marrat Formation is a sharp but conformable lithologic break, a break from shale (or gypsum in the vicinity of Khashm adh Dhibt) above to limestone below. The contact is nowhere exposed north of this area. From Wâdi Birk south, the lower limit becomes less clear as the contact disappears in a monotonous sandstone-shale sequence. Apparently, the Dhurma unconformably overlies the Marrat near Khashm Mâwân (lat 22°50' N.), then rests on progressively older beds of the Minjur and Jilh Formations, butts eventually against the Sudair (near lat 20°00' N.), and wedges out completely between Tuwaiq Mountain and Sudair near Khashm az Zifr (lat 19°30' N.). Loss of Dhurma beds southward over this distance almost certainly takes place at the base as successively younger Dhurma strata lap over progressively older rocks. Further data (from tracing of surface beds and detailed faunal correlations in nearby bore holes) show conclusively that beds are not removed at the top.

The contact with the overlying Tuwaiq Mountain Limestone represents a conformable transition from shale to limestone. The upper Dhurma limit is placed at the change from shale, thin interbeds of calcarenite, and calcarenitic limestone (Dhurma) to soft apatitic and calcarenitic limestone with shale partings (Tuwaiq Mountain). No topographic break marks the contact, but it consistently occurs 30 to 40 m below the base of the massive, cliff-forming phase of the Tuwaiq Mountain Limestone. Relationship to the two formations along strike is maintained with remarkable uniformity. The change from the predominantly clay lithology of the Dhurma to the soft, marly limestone of the basal Tuwaiq Mountain has been mapped from Az Zilft to Al Haddâr. From Al Haddâr south, the contact, although traceable, is obscured as a thin basal Tuwaiq Mountain unit, and most of the Dhurma is replaced by sandstone.

The actual elimination of Dhurma beds north of Az Zilft is masked by the Nafûd ath Thuwayrât and the 'Iqr al Mazhûr. Geometry of adjacent units, however, indicates that the Dhurma is, in fact, cut out by pre-Wasia erosion near the northeastern edge of 'Iqr al Mazhûr (presumably somewhere between long 43°35' E. and 44°10' E.).

PALAEONTOLOGY AND AGE

LOWER DHURMA

Arkell (1952) unhesitatingly places the lower part of the lower Dhurma in the middle Bajocian on the basis of the *Dorsetensis* fauna. His assignment of the *Ermoceras*-bearing beds in the upper Dhibi limestone is somewhat less definite, namely "Early-Upper or late-Middle Bajocian."

This placement of the entire lower Dhurma within the Bajocian presents certain problems when viewed in relationship to the contained foraminiferal faunas. Those faunas of the lower part of the lower Dhurma are rich in members of the Lagenidae; while not as yet worked out in detail, they carry the typical aspect of published faunas from Bajocian and older beds throughout the world. On the other hand, the foraminiferal faunas of the upper part of the Dhibi limestone introduce many of the genera and even a few of the species which characterize the overlying middle Dhurma.

Among the forms which appear in the Dhibi limestone are the following: *Dhurmella evoluta* Redmond, *Haurania amiji* Henson 1948, *Haurania deserti* Henson 1948, *Nautiloculina* spp., *Pfenderina inflata* Redmond, *Pseudomarrsonella primitiva* Redmond, *Riyadhella elongata* Redmond (Redmond, 1965).

All the above genera make their first appearance at this point, some of them to persist through lengthy ranges. On the species level the situation is even more striking because *Pseudomarrsonella primitiva* is abundant in the lower part of the middle Dhurma and *Dhurmella evoluta* and *Riyadhella elongata* range even higher, completely through the lower two zones of the middle Dhurma.

Hudson and Chatton (1959) report the entrance of the genus *Nautiloculina* in the group b beds of the Musandam Limestone, together with *Haurania amiji* Henson and *Haurania* cf. *H. deserti* Henson. After suggesting a correlation between the lower part of the Dhurma Formation and the group b beds on the basis of comparable microfossils and similar stratigraphic position, Hudson and Chatton go on to remark that the type locality of *Haurania amiji* and *Haurania deserti* in Iraq is now considered to be Bathonian in age. In addition to this they correlate the overlying *Haurania amiji*-bearing group c beds with the middle Dhurma.

It would thus appear that the relationship between the group b beds and the group c beds is exactly analogous to the relationship between the lower Dhurma and the middle Dhurma. The lower unit in each instance carries in its upper part faunal elements which range on up into overlying beds of undoubted Bathonian age.

Since the *Ermoceras* faunas of the Dhibi limestone do not appear to range completely to the top of the unit

(see Steineke and Brankamp, 1952b), and in view of the foregoing discussion, it is highly probable that the Bathonian-Bajocian boundary does not coincide exactly with the top of the escarpment-forming lithographic limestone on the uppermost Dhibi but falls somewhere a short distance below.

MIDDLE DHURMA

Arkell (1952) lists the following succession of middle Dhurma ammonite faunas and gives age references.

Top:

Middle (and upper?) Bathonian:

Dhurmaites fauna
Micromphalites fauna
Tulites fauna

Lower Bathonian?:

Thambites fauna

Bottom.

There are at least three major foraminiferal zones in the middle Dhurma, but the exact relationship of these zones to the ammonite faunas is not yet completely clear. It is known, however, that *Dhurmaites* occurs within the upper foraminiferal zone and *Thambites*, within the lower zone, but the placement of the middle ammonite zones within the foraminiferal zones has yet to be established.

In the following lists detailing the more conspicuous microfaunal elements of the middle Dhurma the words "upper", "middle", and "lower" are used purely in the spatial sense and are intended neither as formal zonal designations nor as lithic subdivisions.

The lower part of the middle Dhurma contains *Dhurmella evoluta* Redmond, *Nautiloculina* spp., *Pfenderina* sp., *Pseudomarrsonella meclurei* Redmond, *Pseudomarrsonella primitiva* Redmond, *Riyadhella elongata* Redmond.

The middle part of the middle Dhurma contains *Dhurmella evoluta* Redmond, *Nautiloculina* spp., *Pseudomarrsonella reflexa* Redmond, *Riyadhella elongata* Redmond, *Riyadhella arabica* Redmond, *Virgulina* spp.

The upper part of the middle Dhurma contains *Flabellamina* sp., *Nautiloculina* spp., *Pseudomarrsonella biangulata* Redmond, *Pseudomarrsonella bipartita* Redmond, *Riyadhella inflata* Redmond, *Riyadhella nana* Redmond, *Riyadhella rotundata* Redmond. (See Redmond, 1965.)

UPPER DHURMA

To date no ammonites have been reported from accurately placed positions within the upper Dhurma. Arkell (1952) listed such forms as *Gryphaea costellata* Douville, *Eligmus rolandi* Douville, *Eligmus rolandi* Douville var. *jabbokensis* Cox, *Eudesia cardium* Lamarck and *Eudesia cardioides* Douville from this part of the section and assigned a questioned late Bathonian age to it.

P. M. Kier, E. G. Kaufmann, and others of the Smithsonian Institute are currently studying much more complete megafossil collections obtained in the recent past. The outcome of their work is expected to clear up much of the present uncertainty over the correct age assignment of the various segments of the upper Dhurma, and it would be profitless to debate the matter here. It can be noted, however, that the rich foraminiferal faunas in the upper part of the Hisyan Member are so closely related to those of the immediately overlying middle Callovian lower part of the Tuwaiq Mountain Formation as to suggest a break of less than stage magnitude at the contact. This is particularly true of the highly evolved and closely related Kurnubias occurring on both sides of the contact. In view of these relationships it is suspected that at least the upper part of the Hisyan Member will prove to be no older than Callovian.

A partial list of the Foraminifera occurring within the upper Dhurma (Redmond, 1964a, 1965) is as follows:

'Atash Member (*Indicates occurrence only in lower part of member):

- Kurnubia variabilis* Redmond*
- Nautiloculina* spp.
- Pfenderella arabica* Redmond*
- Pfenderina gracilis* Redmond
- neocomiensis* (Pfender) Smout and Sugden
- trochoidea* Smout and Sugden*
- Pseudomarrasella maxima* Redmond
- plicata* Redmond
- Sanderella laynei* Redmond*
- Trocholina* spp. (including a large, high-spired form with an acute initial end)

In the foregoing list the large, high-spired *Trocholina* represents the lowest occurrence of this type of *Trocholina* in Saudi Arabia. The genus is sparingly represented below this point, but all forms seen to date are small and low spired. Likewise, *Kurnubia variabilis* is the stratigraphically lowest known representative of the genus *Kurnubia*.

Hisyan Member:

Upper part:

- Conicospirulina* sp.
- Kurnubia bramkampi* Redmond
- spp.
- Pseudomarrasella media* Redmond
- Riyadhella* sp.
- Steinekella crusei* Redmond
- Trocholina palastinensis* Henson (1948)
- cf. *T. palastinensis* Henson, "high spired variant"
- (Henson, 1948, pl. 13, fig. 10)

Lower part:

- Kurnubia* spp.
- Prækurnubia crusei* Redmond
- Riyadhella hemeri* Redmond
- Trocholina* sp. (small, flat form with prominent marginal band on ventral surface)

A comprehensive fossil list of the Dhurma Formation includes the following:

Brachiopoda:

- Bikenithyris barringtoni* Muir-Wood
- Burnirhynchia gregoryi*? Wier
- Charltonithyris bikenensis*? Weir
- Dogkanirhynchia daghaniensis* Muir-Wood
- Leobolithyris jubaensis*? Weir
- Parolithyris*? sp.
- "*Rhynchonella*" sp.
- Somalirhynchia bikenensis* Muir-Wood
- Somalithyris* aff. *S. mafjadyeni* Muir-Wood
- Terebratula respai*? Stefanini
- superstes* Douville
- aff. *T. saemanni* Oppel

Coelenterata:

- Amphiasiraea*? sp.
- Anabacia* spp.
- Isaiaea*? sp.
- Isastracoenia*? sp.
- Milleporidium* sp.
- Montilaitia* sp.
- Stylina*? sp.
- Thamnostraea* sp.
- colonial corals undetermined

Echinodermata:

- Acrosalenia somaliensis* Currie
- emilei* Currie
- spp.
- Apiocrinus* aff. *A. roiseyanus* d'Orbigny
- Bothriopneustes somaliensis* Currie
- cf. *B. orientalis* Fourtau
- sp.
- Clypeobrius* sp.
- Holcypus* sp.
- Polycypus* sp.
- Recrosalenia* sp.
- cladroid radloles
- crinoid plates and stems

Foraminifera:

- Ammobaculites* sp.
- Bolivina* sp.
- Conicospirulina* sp.
- Dhurmella evoluta* Redmond
- Flabellamina* sp.
- Gutulina* sp.
- Haplophragmoides* sp.
- Haurania amiji* Henson
- deserti* Henson
- Kurnubia bramkampi* Redmond
- variabilis* Redmond
- spp.
- Lenticulina* sp.
- Marginulina* sp.
- Marginulinopsis* sp.
- Nautiloculina* sp.
- Ophthalmidium* sp.
- Pfenderella arabica* Redmond
- Pfenderina gracilis* Redmond
- inflata* Redmond
- neocomiensis* Smout and Sugden
- trochoidea* Smout and Sugden
- sp.
- Prækurnubia crusei* Redmond

- Pseudocyclamina* sp.
Pseudomarsenella biangulata Redmond
 bipartita Redmond
 maxima Redmond
 neclurei Redmond
 media Redmond
 plicata Redmond
 primitive Redmond
 reflexa Redmond
Pseudoripulina sp.
Riyadhella elongata Redmond
 hemeri Redmond
 inflata Redmond
 nana Redmond
 arabica Redmond
 rotundata Redmond
 sp.
Sanderella laynei Redmond
Spiroculina sp.
Steinekella crusei Redmond
Trocholina palastinensis Henson
 cf. *T. palastinensis* Henson
 sp.
Valvulina sp.
Virgulina sp.
Mollusca:
Acteonina sp.
Ampullella sp.
Anchura (Pietreia)? sp.
Anisocardia sp.
Aporrhaia sp.
Arca sp.
Arcomytilus laumairensis de Loriol
 somaliensis Cox
 sp.
Astarte scytalis Holdhaus
Bakewellia walloni (Lyett)
Bramkampia steinekei Arkell
Bullaria? sp.
Camptonectes cf. *C. browni* Cox
 sp.
Ceratomya wimmisiensis (Gillieron)
 cf. *C. excentrica* (Roemer)
 cf. *C. wimmisiensis* (Gillieron)
 sp.
Ceromyopsis arabica Cox
 cf. *C. somaliensis* Weir
 sp.
Chlamys curvicularia Dietrich
 macfadyeni Cox
 cf. *C. macfadyeni* Cox
 sp.
Clydoniceras pseudodiacus Arkell
Cochleochilus? sp.
Corbula sp.
Crassatellites? sp.
Cylindrites cf. *C. striatus* (Lissajous)
 plicifer Cosman
 sp.
Cylindrites? sp.
Dhrumaites cardioceratoides Arkell
Diacheliz douvillei Cosman
 elegantulum
 cf. *D. elegantulum* Douville
 Diacheliz? sp.
Dorstenia arabica Arkell
Eligmus polytypus (Eudes-Deslongchamps)
 rollandi Douville
 rollandi var. *jabbokensis* Cox
 weiri Cox
 cf. *E. aualites* (Stefanini)
Ermoceras coronatiforme Arkell
 coronatoides (H. Douville)
 elegans H. Douville
 magnificum Arkell
 reineckoides Arkell
 runcinatum Arkell
 splendens Arkell
 strigatum Arkell
 cf. *E. mogharensis* H. Douville
 cf. *E. runcinatum* Arkell
Eudenia cardioides Douville
 cardium (Lamarck)
 sp.
 Globularia sp.
Goniomya? sp.
Gryphaea balli Stefanini
 costellata Douville
Gryphaea? sp.
Homomya inornata (J. de C. Sowerby)
 cf. *H. gibbosa* (J. Sowerby)
 sp.
Isocyprina? sp.
Leda sp.
Lima giganea (Sowerby)
 harronis Dacque
 sp.
Limatula cf. *L. corallina* Arkell
 cf. *L. elliptica* (Whiteaves)
Lopha eruca Cox
 gregaria (Sowerby)
 solitaria (J. de C. Sowerby)
 sp.
Lucina? sp.
lucinoides undetermined
Macromya aequalis Agassiz
 sp.
Micromphalites clydromphalus Arkell
 elegans Arkell
 intermedius Arkell
 pustuliferus (H. Douville)
 vertebralis Arkell
 cf. *M. busqueti* (de Grossouvre)
 sp.
Modiolus imbricatus (Sowerby)
 (*Inoperna*) *plicatus* (J. Sowerby)
 cf. *M. imbricatus* (Sowerby)
 sp.
Mytilus somaliensis Cox
 sp.
Nautilus spp.
Nerinea (Pygmaea) aff. brevisolula Huddleston
 somaliensis Weir
 cf. *N. bathonica* Rigaux and Sauvage
 sp.
Nucleolites sp.
Nucula cuneiformis J. de C. Sowerby
 cf. *N. tenuistriata* J. de C. Sowerby
 sp.

Opis sp.
Ostrea dubiensis Contejean
 sp.
Ozyloma inequivalve (Sowerby)
 sp.
Ozyloma? sp.
Paracnaceras sp.
Pholadomya aubryi Douville
lirata (J. Sowerby)
somalensis Cox
 sp.
Pholadomya? sp.
Pisna sp.
Pinna? sp.
Pleurotomaria sp.
Pleurotomaria? sp.
Protocardia somaliensis Cox
 sp.
Pseudocardia macfadyeni Cox
Pseudotrapezium sp.
Pteria sp.
Pteroperna sp.
Purpuroidea aff. *P. perstriata* Cosman
Stephanoceras arabicum Arkell
 cf. *S. pilicanthus* Wernbter
Strungia arabica Arkell
Teloceras cf. *T. labrum* Buckman
Thambites mirabile Arkell
oxynotus Arkell
planus Arkell
Thamboceras mirabile Arkell
Thracia? sp.
Trigonia sp.
Trochus sp.
Tulites arabicus Arkell
erymnoides Arkell
tuwaiqensis Arkell
Vastites? sp.
 Ostracoda:
Argillacris sp.
Bardia sp.
"Brachygythere" sp.
Gythyropsis sp.
Cytherella sp.
Cytherelloidea spp.
"Cytheridea" sp.
Cytheropteron sp.
Cytherura sp.
Darwinula? sp.
Eocytheropteron? spp.
Eucytherura sp.
"Haplocytheridea" spp.
Hutsonia sp.
"Hutsonia" sp.
Klicana sp.
Leguminocytheris? sp.
Monoceratina sp.
Paracypris spp.
Paraschuleridea spp.
Polyscope sp.
Polycopis sp.
Pontocypris? sp.
Procytheridea spp.

Miscellaneous:

calcareous sponges undetermined
 algal balls

ECONOMIC ASPECTS

GROUND WATER

Only negligible information has been gathered on the ground-water characteristics of the Dhurma Formation. The most promising area appears to be in the southwest where the formation is in porous sandstone facies. A bore hole down dip from Wādī ad Dawāsir yielded large quantities of fresh water from the Dhurma.

PETROLEUM

The few widely scattered wells that have so far penetrated the Middle Jurassic have passed through potentially favorable reservoir units at several levels. The most attractive and widespread of these is the 'Atash Member which is usually found to be at least partly in porous calcarenitic facies. The 'Atash Member (Fadhili reservoir) contains commercial quantities of oil in Fadhili, Khuras, and Qatif fields. Significant shows have been detected in other structures. In addition, the 'Atash is oil bearing in several other fields in the Middle East.

TUWAIQ MOUNTAIN LIMESTONE—UPPER JURASSIC

DEFINITION

The Tuwaiq Mountain Limestone is named for Jabal Tuwayq, the spectacular, nearly parallel sequence of west-facing scarps developed in the Jurassic rocks of central Arabia. The Tuwaiq Mountain Limestone itself supports the largest and most persistent of these escarpments and, as such, constitutes the backbone of Jabal Tuwayq.

Max Steineke in 1937 described and defined the Tuwaiq Mountain Limestone as a member of his Tuwaiq Formation. In 1945 R. A. Bramkamp raised the Tuwaiq Formation to group and elevated the limestone member to formation. The first published reference to Tuwaiq Mountain Limestone was in Arkell (1952) where the type locality was described. These data were repeated without significant change by Steineke, Bramkamp and Sanders (1958).

The type section occurs along the old Darb al Hijāz (Riyadh-Jiddah road) through "Hisiyān Pass" between lat 24°51'56" N. long 46°07'10" E. and lat 24°56'30" N., long 46°13'32" E. A total of 215 m of section was measured and calculated.

At the type area, the base of the Tuwaiq Mountain Limestone is at the contact between soft calcarenitic limestone and underlying olive-green shale of the Dhurma. The upper limit is the contact of massive coral-bearing limestone with overlying marl and soft limestone of the Hanifa Formation.

OCCURRENCE AND THICKNESS

The Tuwaiq Mountain Limestone has been mapped from Huwaymil (near lat 17°30' N.) to lat 27°30' N., a distance of more than 1,200 km. Exposures are almost continuous except for sand cover at 'Irq al Mazhūr, Al Mundafan, and south of Banī Khajmah. From a width of 20 km in central Najd, the outcrop band narrows irregularly to about 10 km at the northern and southern extremities. Although strike of the beds shifts gradually along the outcrop belt, dip remains relatively constant, averaging about 00°40'.

Tuwaiq Mountain Limestone dominates both the stratigraphy and topography of central Arabia. Over most of its extent the limestone forms a precipitous west-facing cuesta, gently bowed in the center and concave toward the west. Differential relief from the top of the scarp to the valley floor in front is more than 500 m in the central area of outcrop. Away from this area, the height of the escarpment diminishes gradually until a low weathered bench of a few meters remains in the extreme north and south at Qibā' and Huwaymil, respectively. The true elevation of the scarp remains relatively constant (about 1,000 m) in the southern and central areas. In the north, however, the top of the limestone cliff uniformly loses elevation and reaches a low of 640 m just before passing under 'Irq al Mazhūr (at lat 26°30' N.).

For all practical purposes, the western boundary of the formation is marked by a vertical limestone cliff which in many places exposes 100 m or more of lower Tuwaiq Mountain strata. An additional 30 to 40 m of Tuwaiq Mountain rocks occurs below the cliff-former, but this is more argillaceous and simply weathers as an extension of the gentle slope established in the underlying Dhurma strata. The upper part of the formation forms a strong plateau surface tilted gently eastward. This surface is not a true dip slope but is slightly beveled so that successively younger beds are present down dip. The eastern margin of the formation is usually marked by a wide flat valley eroded in front of the Hanifa Formation.

In addition to its occurrence in the Tuwaiq scarp, Tuwaiq Mountain Limestone is preserved in Awsat, Durrā, Qarādān, Barrah, and Majma'ah grabens as prominent ridges and erosional remnants. In general, only the upper part of the formation is exposed in these structures, the main exceptions being Barrah, where the basal beds crop out at the ends of the graben, and at the west end of Awsat.

Thickness of the Tuwaiq Mountain Limestone reaches a maximum in the Darb al Hijāz (type locality)-Wādī Nisāh (lat 24°15' N.) area where between 200 and 215 m was measured and calculated. The formation thins uniformly away from this region; to the north,

sections near Al Ghāt (lat 26°02' N.), Az Zilfī (lat 26°18' N.), and Qibā' (lat 27°24' N.) measured respectively 130, 80, and 45 m; and to the south the limestone measured about 150 m at Wādī Birk, 100m at Al Haddār, 80 m in Wādī ad Dawāsir, and 60 m at the southern end of Banī Khajmah.

LITHOLOGIC CHARACTER

Steineke, Bramkamp, and Sander (1955) described the Tuwaiq Mountain Limestone as

a great plate of coral-bearing, dense, pure limestone, at the base of which is a thin noncoraliferous well-bedded chalky unit * * *. In typical Tuwaiq Mountain limestone, coral heads are scattered, commonly in position of growth, but ordinarily they make up only a small proportion of the rock as a whole. Several small reefs up to 15 meters high and about 50 meters in diameter are present just west of Riyadh, but aside from these the unit is thickly, but well, bedded. To the north as far as its most northerly known outcrops near Aqibba [Qibā'] (about Latitude 27°15' North), the Tuwaiq Mountain limestone shows increased inclusion of soft limestone. To the south of the latitude of Riyadh, the unit progressively thins, the proportion of calcarenite increases, and corals become more and more concentrated into rubbly beds in which coral remains make up a substantial proportion of the rock. Branching stromatoporoids, few in the central area, increase in abundance and, in places in the south, become rock forming.

The marked lithologic continuity of the Tuwaiq Mountain Limestone is one of the most spectacular features of the geology of Arabia. In central Najd, the formation is a massively bedded aphanitic limestone with some calcarenitic limestone and calcarenite in the upper part. The lower 25 to 40 m is well-bedded, highly fossiliferous, soft, chalky limestone with some soft calcarenitic limestone, calcarenite, and shale. The lower chalky unit is gradational from Dhurma shale below to massive limestone at the top and forms an even talus slope at the foot of the vertical cliff. The base of the cliff-forming limestone is not a stratigraphic plane. Tracing the "notch" weathered at the junction of the hard and soft beds confirms this observation. Where the basal beds of the limestone become more argillaceous and calcarenitic, the "notch" rises in the section, and vice versa. The typical lithologic-topographic pattern of a shale slope at the base, a limestone cliff above, and a broad, bench-ridden back slope cut in the upper limestone beds maintains itself throughout the outcrop belt.

Because of the limestone's tendency to form sheer cliffs, the only easily accessible full sections of Tuwaiq Mountain Limestone are found along the courses of transverse channels which breach the Tuwaiq front at nearly regular intervals. In these, erosion usually reduces the vertical cliff to steplike talus slopes of about 40°. Complete sections have been measured at each gap, and a few of these have been selected to illustrate

the lateral changes taking place in Tuwaiq Mountain lithology.

Samples from Riyadh water well 1 (lat 24°36'43" N., long 46°40'38" E.) provide the most complete record of Tuwaiq Mountain rocks, and the interval between 217.6 and 420.6 m in depth in this well is herein designated as a reference section (pl. 8). A detailed description and lithologic breakdown made by N. M. Layne and R. W. Powers in 1957 is given in section 31 (p. 132).

The first important change north of the reference locality is detected in the Al Ghāt section where shale appears in the upper part and massive calcarenite beds in the lower. As a result of the introduction of softer beds, the sharp contact with the overlying Hanifa is lost. In 1952 S. J. Roach described and measured the Al Ghāt sequence approximately along lat 26°02' N. The succession is summarized in section 32 (p. 132).

Farther north, in the vicinity of Qibā', the formation is 45 m thick and can be divided into two units. The upper 20 m is mainly soft, chalky limestone containing a diffractive Tuwaiq Mountain fauna. The highest beds are calcarenitic limestone with abundant silicified coral heads. The lower 25 m consists of platy limestone, sandy marl, and a small amount of greenish-yellow shale and, in the lower part, considerable interbedded sandstone. This unit grades rapidly northward to an argillaceous and arenaceous facies.

South of the reference locality, the first basic change in Tuwaiq Mountain rocks is seen just beyond Sha'ib al Haddār (lat 22°00' N.) where the basal few meters of limestone is replaced by sandstone. The sand, with some irregularity in thickness but averaging about 10 m, persists to the southern limit of exposure.

The first significant change in beds above the sand is the appearance of a thick dolomite-calcarenite lens in sections immediately adjacent to Wādī ad Dawāsir. R. A. Bramkamp, B. Beverly, and S. B. Henry in 1954 described a typical sequence in the area at Khashm Fardah (lat 20°12' N.). The succession is summarized in section 33 (p. 132).

Flanking traverses show that the dolomite-calcarenite lens is restricted to the vicinity of Wādī ad Dawāsir and is replaced to the north and south by fine-grained carbonate rocks.

Another major lens of calcarenite, grading in both directions to typical massive aphanitic limestone, occurs in the Al Mundafan area. A section described by Bramkamp and H. A. Kimball in 1950 at the southern tip of the Al 'Arid escarpment (lat 18°33' N.) is characteristic. The sequence is summarized in section 34 (p. 132).

The Tuwaiq Mountain beyond Al Mundafan is again typically aphanitic limestone with a basal unit of sandstone, although important concentrations of calcarenite do occur at several levels.

NATURE OF CONTACT WITH ADJACENT FORMATIONS

The placement of the lower limit of the Tuwaiq Mountain Limestone has evoked as much spirited discussion as any other aspect of Arabian geology. In Max Steineke's original description of the formation in 1937, he did not precisely define the Dhurma-Tuwaiq Mountain contact, although it appears that he considered it to fall at the base of the massive cliff-forming limestone.

R. A. Bramkamp in 1945 found that the fauna for at least some distance below this point was similar to that above. On faunal evidence, he lowered the contact to the upper limit of clay shale which appeared to coincide with the upper limit of *Gryphaea costellata*. In the central Tuwaiq this results in the inclusion of 25 to 40 m of soft, argillaceous limestone (below the main cliff-forming member) within the Tuwaiq Mountain Limestone.

Later work by D. A. Holm and others in 1947 showed the upper range of *Gryphaea costellata* to be erratic. Holm then proposed the Hisyan Member (of the Dhurma) to include all beds between the base of the cliff-forming limestone and the top of what is now defined as the 'Atash Member. A detailed lithologic-paleontologic analysis of the problem by J. S. Cruse in 1961 led to the conclusion that Bramkamp's placement of the contact (as defined in Steineke and others, 1958) was the most logical choice, and no redefinition was necessary. The break is apparent both on surface and in deep wells. Examination of the contact from Az Zilfi in the north to Sha'ib al Haddār in the south has shown it to be mappable. Although the contact is not knife sharp, the transition from upper Dhurma clay to lower Tuwaiq Mountain Limestone takes place in a very narrow zone, and the break can be placed within a few meters with a fair degree of certainty. Consequently, the contact proposed by Bramkamp in 1945 and formalized by Steineke and others (1958) is retained here.

Immediately south of Sha'ib al Haddār, the basal beds of the Tuwaiq Mountain Limestone are replaced by sandstone, a direct reflection of the shift to sandstone in the underlying Dhurma. Thickness of the basal clastic beds never exceeds 17 m and is usually about one-half this figure. Interbeds of calcareous sandstone and sandy limestone and numerous fossils (mostly *Nerinea*) serve to separate the Tuwaiq Mountain from the Dhurma and other sandstones all the way to Al Mutabaṭṭiḥāt (lat 17°47' N.).

The Dhurma-Tuwaik Mountain contact is conformable from Qibā' to Al Haddār. Presumably the contact becomes disconformable between Al Haddār and lat 19°24' N., where the Dhurma pinches out and Tuwaik Mountain rests with low angular discordance on the Sudair Shale. Continued transgression carries the Tuwaik Mountain Limestone across the beveled edges of the Sudair and Khuff Formations, and finally brings the formation into contact with the Wajid at Banī Khatmah.

The Tuwaik Mountain contact with the overlying Hanifa Formation appears to be conformable although there is some evidence, at least on a local scale, that an unconformity separates the two units. Subsurface data support this possibility as pre-Hanifa erosion is demonstrable over several structures in coastal Arabia.

On outcrop, the upper limit of the Tuwaik Mountain is placed at the change from light-colored, massive, resistant, coral-bearing aphanitic limestone below to brown, softer, thin-bedded, noncoraliferous, aphanitic and calcarenitic limestone above. South of Wādī ad Dawāsir, coral heads extend up into the lower Hamifa, but bed tracing, lithologic character, and topographic expression permit placement of the formation boundary. In central and northern Najd, the basal Hanifa limestone is more argillaceous and even contains shale at various localities. The contact is readily recognizable as a white band below brown slopes, the bottom of the white band coinciding with the break. The contact is excellently exposed on either side of Wādī Hanifah near Jabal al Abakkayn (lat 24°58' N.).

The Tuwaik Mountain Limestone is abruptly terminated about 20 km north of Qibā' where it intersects the pre-Wasia erosion surface.

PALAEONTOLOGY AND AGE

The lower beds of the Tuwaik Mountain Limestone were assigned to the middle Callovian *coronatum* zone by Arkell (1952) on the basis of contained ammonites. They also contain fairly abundant foraminiferal faunas including *Trocholina palastinensis* Henson and several undescribed species of *Kurnubia*.

The middle and upper parts of the Tuwaik Mountain Limestone are lacking in ammonites but contain two distinctive Foraminifera: *Kurnubia wellingsi* (Henson) and *Steinekella steinekei* Redmond (Redmond, 1964). As yet, there is no record of the latter form outside of Saudi Arabia, but *Kurnubia wellingsi* was described from the Kurnub anticline where it occurs in beds which Hudson and Chatton (1959) consider to be of Oxfordian (Argovian) age.

Where the Tuwaik Mountain is present in full development, *Steinekella steinekei* and *Kurnubia wellingsi* do not range to the top of the formation. The

uppermost beds are poor in Foraminifera but carry fragments of a *Kurnubia* which very possibly represents *Kurnubia jurassica* (Henson).

A comprehensive list of fossils recovered from the Tuwaik Mountain Limestone includes:

- Brachiopoda
 - Rhynchonella* sp.
 - Somalirhynchia bihenensis* Muir-Wood
 - Terebratula* cf. *T. bicanaliculata* Schlotheim sp.
- Coelenterata:
 - Anabacia* sp.
 - Milleporidium*? sp.
 - Thamnastraea* sp.
 - colonial and solitary corals undetermined
- Echinodermata:
 - Apiocrinus* sp.
 - crinoid stems and plates
- Foraminifera:
 - Conicospirulina* sp.
 - Guttulina* sp.
 - Haplophragmoides* sp.
 - Kurnubia jurassica* (Henson)
 - wellingsi* (Henson) sp.
 - Lenticulina* sp.
 - Marginulina* sp.
 - Marginulinopsis* sp.
 - Nautiloculina* sp.
 - Steinekella steinekei* Redmond
 - Trocholina palastinensis* Henson sp.
 - Valutina* sp.
- Mollusca:
 - Acteonina* sp.
 - Aequipecten macfadyeni* Cox
 - Ampullitella* sp.
 - Aniscardina* sp.
 - Aporrhaia* sp.
 - Arcomytilus*
 - "*Cardium*" sp.
 - Ceratoma vimensis* (Gillieron) sp.
 - cf. *C. plicata* (Agassiz)
 - Ceromyopsis arabica* Cox sp.
 - Chlamys curvisariana* Dietrich
 - macfadyeni* Cox sp.
 - Cylichna* sp.
 - Cylindrites plicifer* Cosman
 - Discochelis douvillei* Cosman sp.
 - Elasmus rollandi* var. *jabbokensis* Cox sp.
 - Erymnoceras philbyi* Arkell
 - cf. *E. philbyi* Arkell
 - cf. *E. jarryi* (R. Douville)
 - aff. *E. triplicatum* (Till)
 - Ezogyra nana* (Sowerby) sp.
 - Globularia hemispherica* Roemer sp.

- Gryphaea balli* (Stefanini)
sp.
Homomya inornata Sowerby
sp.
Lima harronisi Dacque
sp.
Lepha solitaria (J. de C. Sowerby)
eruca Cox
sp.
Modiolus imbricatus (Sowerby)
(*Inoperna*) *plicatus* (J. de C. Sowerby)
sp.
Mytilus (*Arcomytilus*) *somaliensis* Cox
cf. *M. imbricatus* (Sowerby)
sp.
Nerinea cf. *N. bathonica* Rigaux and Sauvage
sp.
Ostrea spp.
Oxytoma inequivalve (Sowerby)
Pachyceras cf. *P. schloenbachii* (Roman)
Paraceras spp.
Pholadomya *avbryi* Douvillé
lirata (J. de C. Sowerby)
somaliensis Cox
sp.
Pinna sp.
Pleuromaria? sp.
Pseudomaria? sp.
Stylina cf. *S. macfadyeni* Thomas
sp.
Stylomilvia cf. *S. sctoradiata*
Subgrossouria? sp.
- Ostracoda:
Bairdia spp.
Cytherella sp.
Cytherelloidea sp.
"Hudsonia" spp.
Paracypris? sp.
Paraschuleridea sp.
Procytheridea spp.
- Plant remains:
Bennettitales sp.
Ginkgoales sp.
- Miscellaneous:
calcareous sponges, echinoids undetermined, cidaroid
radiolites, corals undetermined

ECONOMIC ASPECTS

PETROLEUM

Commercial quantities of oil has been discovered at two levels within the Tuwaiq Mountain Limestone. At Abu Hadiya, oil occurs in the upper 160 ft of the formation in a porous limestone-calcareous sequence—the Hadiya reservoir. In addition, the basal part of the formation contains oil on the crestal part of Fadhilli field and at Qatif where some porosity develops through the introduction of calcarenitic limestone and calcarenite. This porous buildup forms the upper part of the Fadhilli reservoir, a zone falling mainly within the upper Dhurma.

HANIFA FORMATION—UPPER JURASSIC

DEFINITION

The Hanifa Formation takes its name from Wādī Hanifah where the type section was measured (near lat 24°56' N.).

Max Steineke in 1937 first defined the Hanifa as a member of the Tuwaiq Mountain Limestone. The member was raised to formal status by R. A. Bramkamp in 1945 and included in the Tuwaiq Mountain Group. With formal publication of Arabian stratigraphic nomenclature in 1952, the term "Tuwaiq Mountain Group" was discarded, and the term "Hanifa" was retained at formational rank. Detailed definition appeared later the same year and in 1958 in articles respectively by Steineke and Bramkamp (1952b) and Steineke and others (1958).

The 101 m of Hanifa designated as the type section was measured over an 8-km traverse along the north side of Wādī Hanifah (from lat 24°57'24" N., long 46°12'48" E. to lat 24°55'12" N., long 46°17'12" E.).

At the type locality, the base is at the contact between massive, resistant, coral-bearing Tuwaiq Mountain Limestone below and soft, chippy-weathering, calcareous(?) shale of the Hanifa above. The top is at the break from clean-washed, tightly cemented, oolite-pellet calcarenite of the Hanifa below to slabby-weathering, aphanitic and calcarenitic limestone of the Jubaila Limestone above.

OCCURRENCE AND THICKNESS

The Hanifa Formation crops out in a narrow, gently curving belt from Nafūd ath Thuwayrāt (lat 26°32' N.) to Banī Khāṭmah (lat 17°50' N.). Over this 1,100-km distance, width of outcrop varies from 0 to 25 km but averages about 10 km. Exposures are almost continuous north of Wādī al Fāw (lat 19°53' N.). Below the wādī, however, sand ridges on the back slope of the Tuwayq escarpment and a major concentration of sand at Al Mundafan break the outcrop pattern into a series of isolated strike patches.

Continuity of the Hanifa is disrupted in the Wādī Nisāb-Dūrmā area and again near Al Majma'ah (lat 25°50' N.) by elements of the central Arabian graben system. In the central area, prominent linear channels of the Nisāb, Awsāt and Dūrmā grabens slice through the backbone of Jabal Tuwayq and offset the various Jurassic units. In the region of Al Majma'ah (lat 25°55' N.), the persistent trough of the Majma'ah graben disrupts the Hanifa as well as bracketing formations. This structure cuts through the Tuwayq escarpment due east of Al Jurayfah and forms a series of en echelon valleys across the upland surface. The valleys, about 60 m deep in the Tuwayq area, become gradually shallower after breaking through

the main scarp and lose their topographic distinctiveness in the Cretaceous northeast of Az Zilfi.

The Hanifa is a unit of relatively soft rocks plastered on the resistant Jabal Tuwayq plateau and protected above by harder rocks of the Jubaila Formation. In the central area, the lower part of the unit weathers to a long shallow trough. The east flank of the trough is marked by a steep scarp in which most of the formation is exposed; the west edge is commonly limited by a low irregular scarp cut in basal Hanifa beds. Rounded outliers of Hanifa are scattered on the Tuwayq Mountain Limestone surface west of the valley. From Huraymilā (lat 25°07' N.) northward, the topography is no longer dominated by a single Jubaila-capped scarp but gives way to more intricately dissected multiple benches. In the south, the more prominent Hanifa benches break down in the vicinity of Wādī al Ḥamr (lat 22°21' N.) and grade beyond to a step-like series of low-relief cuestas.

Thickness of the Hanifa Formation remains remarkably constant throughout and is, without doubt, the most consistent of all Jurassic units. In the 400 km from Wādī al 'Atk (lat 25°25' N.) to Sha'ib al Haddār (lat 21°55' N.), the formation shows only a 10-m variation in thickness—from 106 to 116 m. Some thinning is evident to the north and south, but even this is limited to a very few meters.

In the vicinity of Al Ghāt the upper Hanifa limit cannot be definitely placed; however, at least 60 m of section can be assigned to the formation with certainty. South of Sha'ib al Haddār, thickness is gradually reduced to 75 m at Wādī ad Dawāsīr. Beyond, there is apparently no appreciable change as measurements vary only from 75 to 82 m.

LITHOLOGIC CHARACTER

Lithologically, the Hanifa Formation is somewhat more variable than the underlying Tuwayq Mountain Limestone; basically, it is another nearly pure carbonate unit. The Hanifa is made up of alternating aphanitic and calcarenitic limestone, much of it oolitic. Beds of golden-brown, oolite calcarenite occur at several levels and become increasingly prominent in the upper part of the formation. In fact, the top of the Hanifa is marked by a massive bed of oolite-pellet calcarenite that can be traced without interruption almost the entire length of the outcrop. In some sections in the north and south calcarenite increases in amount until it becomes the dominant type present. Argillaceous limestone units and some shale are present, particularly in the northern area; dolomite is common in the south. A few coral-bearing beds occur in the central area and become increasingly prominent southward.

The golden-brown calcarenite beds, although thin, are ordinarily resistant and form obvious benches or weather to slabby debris. Generally the Hanifa is sufficiently covered with fragments of this calcarenite so that the entire interval appears brown from a distance, in strong contrast to the lighter colored formations above and below.

Accessibility to Hanifa sections is limited, for the most part, to areas where Jabal Tuwayq has been breached by through-cutting channels such as Wādī ad Dawāsīr, Wādī al Fāw, Sha'ib al Haddār, Wādī Birk, Wādī Nisāb, Wādī Ḥanifah, and Wādī al 'Atk. Full Hanifa sequences have been measured at each of these cuts and at a few other places where terrain permits.

Characteristics of the Hanifa can be adequately demonstrated by only a few sections because of the small changes in lithology and thickness along strike. In the central area, Jabal al Abakkayn affords the cleanest and most accessible place to study the formation in its entirety. Here, contacts with adjacent formations are clearly visible. Jabal al Abakkayn, immediately north of the original type locality, was worked in detail by R. W. Powers and others in 1953, and the resulting measurement has been designated a reference section for the Hanifa Formation (fig. 5). The measurement was made in a continuous traverse between lat 24°57'48" N., long 46°11'28" E. and lat 24°57'54" N., long 46°13'41" E. A detailed description of the sequence is given in section 35 (p. 133).

The Hanifa at Wādī al 'Atk shows virtually the same proportion and distribution of rock types as the reference section. Further north, however, in the vicinity of Al Ghāt, some lateral variation toward increasing calcarenite and addition of dolomite can be observed. S. J. Roach measured the Hanifa approximately along lat 26°03' N. in 1952; the succession is summarized in section 36, (p. 133).

Between Jabal al Abakkayn and Wādī al Fāw (lat 19°53' N.), the Hanifa undergoes little change except for variation in the ratio of clean-washed calcarenite to mud-based carbonate rock and the replacement of some limestone by dolomite at Wādī ad Dawāsīr. Below Wādī al Fāw there is a decided buildup in calcarenite, the maximum occurring at the southern end of the Al 'Arid, escarpment. A section measured by R. A. Bramkamp and others in 1950 near Khashm al Farā'id (lat 18°36' N.) typifies this increase in clean, current-washed carbonate. The Hanifa sequence here is summarized in section 37 (p. 134).

The introduction of dolomite near the top of the Khashm al Farā'id section is accompanied by the almost complete loss of the calcarenite unit that so distinctly marks the upper contact to the north. South of Al

Location:

24°57'48" to 24°57'54"
46°11'28" to 46°13'41"

Generalized lithology

Diagnostic fossils

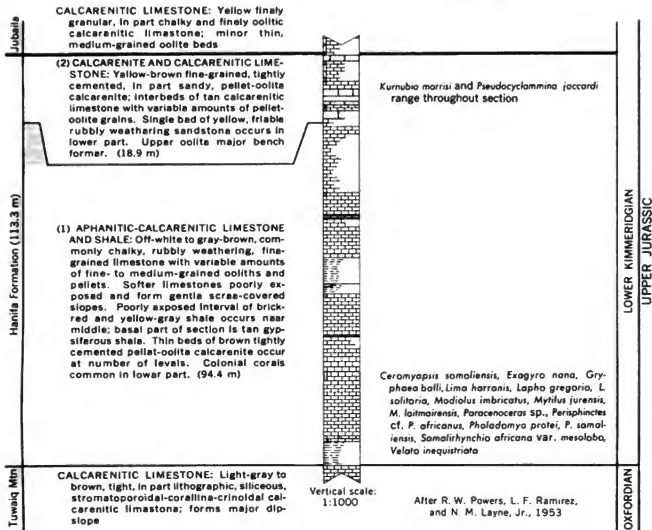


FIGURE 5.—Hanifa Formation reference section.

Mundafan, the dolomite gradually expands at the expense of other carbonates until, at Bani Khatmah, the upper 35 m of an 82-m section is replaced. The lower 47 m shows considerable change as well and is mainly aphanitic and calcarenitic limestone; less than 15 percent of the sequence is clean calcarenite.

NATURE OF CONTACT WITH ADJACENT FORMATIONS

The character of the lower Hanifa contact has already been discussed in the section on Tuwaiq Mountain Limestone.

The conformable contact between the Hanifa and overlying Jubaila is somewhat more difficult to place

than the lower limit; however, it has been fairly accurately traced on photographs and by following beds except at the far ends of the outcrop where dolomite replacement obscures the break. In Najd the upper contact is relatively obvious. The distinctive brown color of the Hanifa rocks, the capping unit of which is a characteristic gray-brown, tightly cemented, pellet-oolite calcarenite, contrasts sharply with the light-colored, usually cliff-forming, somewhat more thinly bedded limestone of the overlying Jubaila Limestone.

The general lithologic-topographic definition of the upper contact persists to Sha'ib al Haddar. Between

Al Haddār and Wādī ad Dawāsir, a major lens of marine sandstone appears in the lower part of the Jubaila. Consequently, in this area the contact is sharply marked by a change from gray-brown, pellet-oilite calcarenite below to brown, medium-grained, moderately cemented, fossiliferous, calcareous quartz sandstone above. South of Wādī ad Dawāsir, the contact is once again pellet-oilite calcarenite overlain by muddy limestone of the Jubaila. This lithologic sequence gives way from Khashm al Farā'id southward where dolomite replaces both upper Hanifa and lower Jubaila strata and the contact can only be approximately placed by continuous bed traces.

Presumably, the Hanifa is terminated on the north by pre-Wasiah erosion, although the actual line of cutting is masked by the Naḥd ath Thuwayrāt.

PALEONTOLOGY AND AGE

Both *Kurnubia morrisi* Redmond (Redmond, 1964a) and *Pseudocyclammina jaccardi* (Schrodt) (= *Pseudocyclammina sequana* of authors) range throughout the Hanifa Formation and into the lower part of the overlying Jubaila Limestone. The biozone of *Pseudocyclammina jaccardi* has been established by Maync (1960) as upper Oxfordian through lower Kimmeridgian. At first glance this would appear to fit well with Arkell's lower Kimmeridgian determination for ammonites in the lower part of the Jubaila outcrop and with Hudson and Chatton's (1959) assignment of their Musandam Limestone group f beds (which they consider equivalent to the Hanifa Formation) to the lower part of the upper Oxfordian.

Although there does not seem to be any reason for challenging Hudson and Chatton's correlation (1959) of the group f beds with the Hanifa Formation, there is some reason to reexamine the evidence which led them to assign the group f beds to the Oxfordian. As noted by Hudson and Chatton, the evidence for this age assignment was entirely indirect; it was based upon a supposed occurrence of *Kurnubia wellingsi* (Henson) in the group f beds and a consequent correlation with *Kurnubia wellingsi*-bearing beds of known Oxfordian age in the Kurnub anticline.

Hudson and Chatton also list *Pseudocyclammina jaccardi* (as *Pseudocyclammina sequana*) from the group f beds. Inasmuch as the ranges of *Pseudocyclammina jaccardi* and *Kurnubia wellingsi* do not overlap each other in the Saudi Arabian section, the former occurring no lower than the base of the Hanifa Formation and the latter occurring no higher than the top of the Tuwaiq Mountain Limestone, the identity of the supposed *Kurnubia wellingsi* in the group f beds becomes somewhat suspect. In this respect it may be pointed out that transverse sections of *Kurnubia*

morrisi closely resemble similarly oriented sections of *Kurnubia wellingsi*, and since *Kurnubia morrisi* and *Pseudocyclammina jaccardi* occur together in the Saudi Arabian section, there is a strong possibility that they do so also in the group f beds and that the reported *Kurnubia wellingsi* occurrences in reality represent *Kurnubia morrisi*.

This situation would remove the necessity for placing the Hanifa Formation within the Oxfordian and open the way for a different correlation derived from deep-well information.

Recent work has demonstrated the presence of both lower Jubaila and upper Hanifa beds at Fadhili field. These are underlain in turn by a series of black shales and black impure limestones which carry an ammonite fauna unanimously identified as lower Kimmeridgian by W. J. Arkell, R. W. Imlay, and Mueller (written commun. in 1951, 1961, and 1960, respectively). There appears to be no question that the black shale and limestone unit represents a facies variant from the normal lower Hanifa lithology and that much if not all of the Hanifa Formation must be placed within the lower Kimmeridgian.

A comprehensive faunal list for the Hanifa Formation includes:

Brachiopoda:

- "*Rhynchonella*" sp.
- Semalirhynchia bikenensis* Muir-Wood
- africana* Weir var. *mesoloba* Muir-Wood
- "*Terebratula*" spp.

Coelenterata:

- Milleporidium* sp.

Echinodermata:

- Acrosalenia? smelliei* Currie
- Goniopygus? sp.*
- Reccosalenia? sp.*

Foraminifera:

- Arenobulimina* sp.
- Cyclammina* sp.
- "*Haplophragmoides*" sp.
- Trachammina* sp.
- Pseudocyclammina jaccardi* (Schrodt)
- Kurnubia morrisi* Redmond

Mollusca:

- Acquiptecten macfadyeni* Cox
- "*Arca*" sp.
- Ampullella* sp.
- Ceratomya* sp.
- cf. *C. telluris* (Lamarck) Cox
- Ceratomya somaliensis* Weir
- spp.
- Chlamys macfadyeni* Cox
- Cosmoeria? sp.*
- Diplodonta? sp.*
- Discodelph* sp.
- Exogyra nana* (Sowerby)
- Globularia hemisphaerica? Roemer*
- Gryphaea balli* (Stefanini)
- Homomya* sp.

Latomeandra sp.
Lima harronii Dacque
Lophia solitaria (J. de C. Sowerby)
gregaria (Sowerby)
Mrandrarea somalica? Thomas
Macromya aequalis Agassiz
 sp.
Modiolus imbricatus (Sowerby)
Mytilus jurensis Roemer
somaliensis Cox
 spp.
Nerinea spp.
Ostrea sp.
Paracnoceras sp.
Pholadomya protei (Brongniart)
 sp.
Pleurodromaria? sp.
Pteroperna sp.
Stylina? cf. *macfadyeni* Thomas
Stylosmilix sp.
Velata inequistrata (d'Orbigny)

ECONOMIC ASPECTS

GROUND WATER

Shallow, hand-dug wells occur sporadically throughout the Hanifa outcrop belt. For the most part, these wells produce from surficial alluvial deposits, but, in some instances, near-surface permeability caused by weathering has permitted the storage and production of meteoric water.

PETROLEUM

The upper 200 to 300 ft of the Hanifa Formation contains commercial quantities of oil at Abqaiq, Abu Hadriya, Khurais, and Khursaniyah. In each locality, the reservoir is porous calcarenitic limestone and calcarenite. Originally referred to as the "mid-Jubaila zone," the productive interval has now been identified as uppermost Hanifa.

JUBAILA LIMESTONE—UPPER JURASSIC

DEFINITION

The Jubaila Limestone derives its name from the town of Al Jubaylah (lat 24°53' N.) near the type locality.

Steineke in 1937 proposed the name to cover the relatively resistant limestone between the softer beds of the Hanifa Formation below and the lower Riyadh Formation (obsolete) above. He designated the Jubaila as a member of the Tuwaiq Formation of Burchfiel and Hoover. In 1945, Bramkamp advanced the rank of the Jubaila and Tuwaiq to formation and group respectively. Names of many of the Arabian rock units, including the Jubaila, were first published in 1952 (Steineke and Bramkamp, 1952a). At this time, the term Tuwaiq Group was dropped from the nomenclature. Particulars of the type section appeared almost immediately thereafter (Steineke and Bram-

kamp, 1952b). They were again published without significant change by Steineke, Bramkamp, and Sander (1958).

The lower part of the type section (about 85 m) was measured along Wādī Hanifah from lat 24°53'48" N., long 46°19'38" E. to lat 24°53'12" N., long 46°26'42" E., a point near the town of Al Jubaylah. The upper 25 m was studied in Wādī Hanifah between Al Jubaylah and Riyadh.

At the type locality the base of the Jubaila is placed at the level where cream to tan, dense limestone gives way downward to the gray-brown pellet-oolite calcarenite of the underlying Hanifa Formation. The top is at the change from brown, ledge-forming limestone below to gray, softer, rubbly-weathering dolomite and limestone of the Arab Formation above.

OCCURRENCE AND THICKNESS

The Jubaila Limestone conforms perfectly to the outcrop pattern of older Jurassic units; that is, it forms a gently curving arc wrapped around the central Arabian arch, reversing itself south of Wādī ad Dawāsir to define the southwest margin of the Rub' al Khālī basin. Rocks of the Jubaila have been mapped over a distance of nearly 1,100 km from Al Munbaṭiḥ (lat 17°41' N.) to Nafad ath Thuwayrāt (lat 26°27' N.). South of Wādī al Fāw (lat 19°57' N.), the Jubaila forms a series of patches isolated by tongues of sand encroaching from the Rub' al Khālī; northward, exposures are almost continuous, although sharply interrupted where the Nisāb, Awsat, and Majma' ah grabens cut through.

Width of the Jubaila outcrop belt varies from a few kilometers at each end to more than 40 km in the central area. Changes in width away from the central area are irregular but nonetheless show unmistakable tapering overall.

The Jubaila Limestone, an extremely resistant limestone sandwiched between two softer units, typically weathers to a series of high, talus-free steps. Lower beds form a prominent scarp, often more than 75 m high, capping the Hanifa. The upper Jubaila breaks away to a gently eastward-tilted plateau which is a slightly beveled upland surface rather than a true dip slope. Consequently, the western margin of the formation is a sharp scarp; the eastern boundary is less regularly defined by patches of the Arab Formation erratically scattered on the strong Jubaila slope.

A short distance north of the type locality, the strong western scarp and high relief is somewhat modified as the Jubaila breaks down into two or three lower benches. The highest of these has an elevation of 30 m at Wādī al 'Atk. From here, relief within the formation diminishes gradually to the northwest. In the south, the Jubaila forms low benches with intervening

wide, slightly eastward-dipping slopes. Scarps are relatively subdued, usually less than 5 m high, although a fairly bold escarpment occurs at Wādī ad Dawāsīr (that is, Khashm ash Shidād, lat 20°26' N.).

The Jubaila Limestone shows some more drastic variations in thickness than other Jurassic units. Maximum thickness of 130 to 145 m occurs in the Sha'tb al Haddār-Wādī ad Dawāsīr area; about 85 and 55 m were recorded respectively at Wādī al Fāw and in a bore hole at lat 18°08' N., long 46°05' E. North of Sha'tb al Haddār the Jubaila thins to about 90 m at Wādī Birk, expands to nearly 130 m at Wādī Nisāb and Riyadh, and then gradually reduces to 110 m at Jabal al Abakkayn (lat 24°58' N.) and 72 m at Wādī Huraymilā (lat 25°07' N.). Partial sections measured beyond this point indicate only slight depositional thinning to the northwest; however, in the vicinity of Al Majma'ah (lat 25°55' N.), pre-Wasia truncation comes into play and upper layers of the Jubaila are planed off. The northernmost measurement near Al Ghāt (lat 26°02' N.) shows but 40 m of section between the presumed top of the Hanifa and the Wasia Formation (Middle Cretaceous).

LITHOLOGIC CHARACTER

The Jubaila Limestone, like the underlying Tuwaiq Mountain and Hanifa Formations, is basically a shallow-water carbonate unit. Though it is mostly aphanitic and calcarenitic limestone, some highly persistent layers of clean-washed lime sand (calcarenite) are present, particularly in the central and northern areas. Corals and stromatoporoids, few in the Riyadh-Durmā area, become abundant to the north and south. Marked lateral changes in the Jubaila to the south consist of a sudden shift from limestone to dolomite in the upper part of the formation and limestone to sandstone and back to limestone again in the lower part. Similar, but less abrupt, limestone transition to dolomite and sandstone also takes place to the north.

Jubaila lithology shows relatively little change from Sha'tb al Haddār nearly to Huraymilā. Over this 370-km distance, the Jubaila is well exposed in many areas, but one of the most accessible and best sections is that at Wādī Nisāb, herewith designated as a reference section (fig. 6) to supplement less detailed work at the type locality. The whole sequence, however, was not measured at a single locality but must be pieced together from three sections. The lower 21.5 m was described (at lat 24°13'22" N., long 46°41'55" E.) by E. L. Berg and R. L. Myers in 1945, the middle 30.8 m was covered (at lat 24°14'55" N., long 46°44'39" E.) by R. A. Bramkamp and S. B. Henry in 1948, and the upper 68.5 m was measured (at lat 24°13'24" N., long 46°48'59" E.) by R. W. Powers and H. A. McClure in

1961. A complete description of the Jubaila sequence in Wādī Nisāb is given in section 38 (p. 134).

Significant changes in Jubaila lithology north of the reference section first appear in the vicinity of Wādī Huraymilā (lat 25°07' N.). At this latitude, the upper part of the formation is mostly replaced by dolomite, and some clean sandstone occurs near the middle. In 1952, R. A. Bramkamp and S. J. Roach measured the Jubaila in the wādī; their description is summarized in section 39 (p. 134).

Little additional change takes place between Wādī Huraymilā and Wādī al 'Atk, but beyond there is a decided increase in sandstone; dolomite makes up the remainder of the sequence. About 50 m of Jubaila is present a few kilometers south of Al Ghāt. The lower one-third and a capping 5- to 10-m bed consists of reddish-brown dolomite; the rest of the section is mainly tan to brown, coarse-grained, calcareous cemented sandstone.

South of the reference locality, the first notable change in Jubaila rocks takes place near Sha'tb al Haddār. The shift can first be seen just north of the sha'tb where a few sandstone interbeds are present near the middle of the formation. South of the sha'tb, near lat 21°50' N., sandstone dominates the lower part of the Jubaila; the upper one-half is partly replaced by thick-bedded dolomite. Almost complete dolomite replacement of the upper limestone of the Jubaila occurs in the vicinity of Wādī ash Shu'tbah (lat 21°30' N.). The lithologic pattern of dolomite above and sandstone below, that persists for at least 150 km, may be characterized by a section measured along lat 20°37' N. The sequence here is summarized in section 40 (p. 135).

The dolomite-sandstone facies can be traced without interruption beyond Wādī ad Dawāsīr, but near Al Hasi (lat 20°08' N.) all sandstone is abruptly replaced by aphanitic limestone. From this point to where the Jubaila disappears under the Rub' al Khāl sand, dolomite and aphanitic limestone are the only rock types. Dolomite does shift stratigraphically downward along strike, however, replacing the upper Jubaila in the north and the lower part of the sequence in the south.

NATURE OF CONTACT WITH ADJACENT FORMATIONS

Characteristics of the conformable contact between the Jubaila Limestone and the underlying Hanifa Formation have been described in connection with the Hanifa.

The upper limit of the Jubaila is a sharp lithologic and topographic boundary. A pattern which maintains itself for more than 700 km starts at the base with a thin calcarenite (unit 3, fig. 6) overlain by 6 to 10 m of gray, tight, chippy-weathering aphanitic limestone

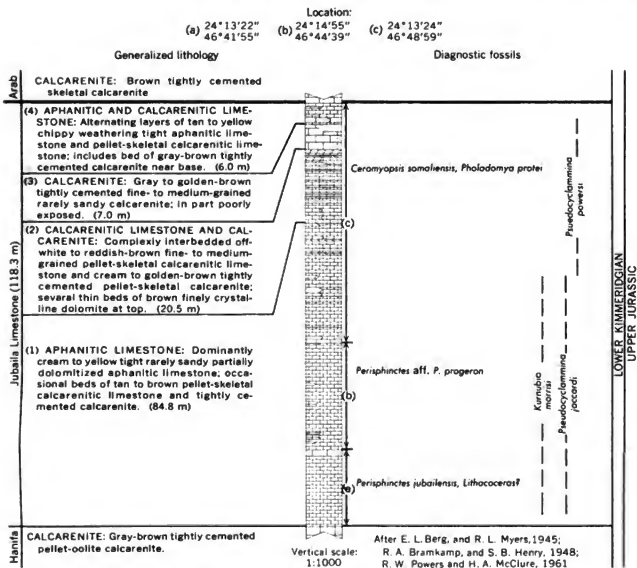


FIGURE 6.—Jubaila Limestone reference section.

locally with interbeds of calcarenite and calcarenitic limestone (unit 4, fig. 6). The top of this lime-mud interval marks the conformable contact of the Jubaila and Arab Formations. Above is a light-colored unit of softer rocks, commonly complexly interbedded aphanitic limestone and calcarenite, which in turn overlain by breccia presumably representing the residuum after solution of a thin anhydrite bed.

The uppermost Jubaila unit of aphanitic limestone commonly weathers to a resistant dip slope. At the foot of this gentle slope is an irregular, highly discontinuous band of softer gray carbonates of the Arab Formation. Solution alteration of the Jabal Tuwayq upland surface locally obscures the upper contact, a

phenomenon that does serve a useful purpose, however, as it permits easy photodistinction between the contorted beds of the Arab Formation and the flat, undisturbed Jubaila surface.

Much of the lithologic pattern so characteristic of beds bracketing the Jubaila-Arab contact on outcrop can be recognized in the subsurface sequence. This is particularly true of the aphanitic bed at the top of the Jubaila, which is equally obvious in the surface and subsurface. This unit corresponds to the middle Arab-D member (Powers, 1962) that subdivides the prolific Arab-D reservoir in Ghawar and other coastal oil fields. The widespread distribution of this muddy limestone and the more fragmental carbonate units flanking it

attest to changes that must have influenced sedimentation over much of the basin so far studied.

PALaeONTOLOGY AND AGE

Arkell (1952) places the Jubaila Limestone in the lower Kimmeridgian on the basis of the perisphinctid ammonites *Perisphinctes jubailensis* Arkell and *Perisphinctes* aff. *P. progeron* von Ammon.

Kurnubia morrisi Redmond and *Pseudocyclammina jaccardi* (Schrodt) occur at the same level as the ammonites. The presence of *Pseudocyclammina jaccardi* fits in well with Arkell's determination since this foraminifer is known to range from the upper Oxfordian into the lower Kimmeridgian.

Pseudocyclammina poversi Redmond occurs in the upper part of the formation, above the range of *Pseudocyclammina jaccardi*. The beds carrying *Pseudocyclammina poversi* likewise fall within the lower Kimmeridgian, if Hudson and Chatton (1959) are correct in equating the stratigraphically higher group g Ashab limestone with the *Cidaris glandarius* beds of the Lebanon and Kurnub areas.

A comprehensive fossil list of Jubaila includes: *Mileporidium*, indeterminate colonial coral, *Kurnubia* spp., *Kurnubia morrisi* Redmond, *Pseudocyclammina poversi* Redmond, *Pseudocyclammina jaccardi* (Schrodt), *Amputella?* sp., *Acicula* sp., *Brachidontes* sp., *Ceratomya* spp., *Ceromyopsis somaliensis* Weir, *Ceromyopsis* sp., *Globularia hemisphaerica* Roemer, *Gryphaea balls?* (Stefanini), *Lithaceras?* sp., *Lucina* sp., *Mytilus* (*Arcomytilus*) *laimmairensis* de Loriol, *Nautilus?* sp., *Nerinea* sp., *Parallelodon?* sp., *Perisphinctes jubailensis* Arkell, *Perisphinctes* aff. *P. progeron* von Ammon, *Pholadomya* spp., *Terebratula* spp., and indeterminate ostracids.

ECONOMIC ASPECTS

GROUND WATER

A number of drilled wells in and near the capital city of Riyadh have penetrated the Jubaila Limestone. Several of these produce from thick Triassic sand, others derive water from channel fill; the amount actually obtained from the Jubaila is unknown.

For many years Riyadh obtained its water from the channel gravels in Wādī Hanifah. This source has now been supplemented by shallow wells in Wādī Nisāh and other nearby channels and deep drilling near the city itself. Limited data indicate that hand-dug wells in the vicinity of Riyadh are bottomed both in the Arab and Jubaila Formations. These two units are relatively tight here, but weathering extends to a considerable depth and jointing is fairly well developed. Apparently, Jubaila water is mainly derived from openings resulting from weathering and jointing, rather than from porosity inherent in the rocks themselves.

PETROLEUM

Porous beds within the upper part of the Jubaila Limestone contain prolific amounts of oil in eight widely scattered fields—Dammam, Abqaiq, Ghawar, Qatif, Abū Sa'fah, Khursaniyah, Fadhili, and Khurais. Stratigraphically, the top of the Jubaila falls near the middle of the well-known Arab-D reservoir.

Areas of maximum oil accumulation and highest productivity correspond rather closely to areas of maximum calcarenite deposition. Pores, now oil filled, are essentially those formed between lime sand grains at the time of deposition and have since undergone little modification. Little or no pore space is contributed to the Jubaila part of the reservoir by dolomite.

ARAB FORMATION—UPPER JURASSIC

DEFINITION

Lack of suitable exposures precluded choice of a surface type locality and the coupling of a geographic name to the economically important rock sequence that has come to be known by the general term Arab Formation.

Beds now assigned to the Arab were originally in 1937 included by Max Steineke as part of the Riyadh Member, the uppermost member of the Tuwaiq Formation. In 1938, R. A. Bramkamp and T. C. Barger studied the upper part of the Riyadh Formation and defined members within it. From bottom to top these were lower Riyadh (now Arab) Formation, Hith Anhydrite, Sulaiy Limestone, and Yamama detrital member.

The finding of presumed Lower Cretaceous (Neocomian) fossils in the Sulaiy led Steineke in 1940 to restrict the Riyadh Formation to include only the lower Riyadh formation and Hith Anhydrite and throw the Sulaiy and Yamama members into a new formation—the Thamama—shown to be at least mainly of Lower Cretaceous age. In 1945, Bramkamp raised the Riyadh to group and its members to formation; that is, Arab and Hith Formations.

Formal publication of most names of Arabian rock units came in 1952b (Steineke and Bramkamp). This paper substituted the term Arab Formation for lower Riyadh Formation (obsolete), but retained the Riyadh Group. Later this too was dropped (Steineke and others, 1958), and Arabian stratigraphic nomenclature assumed its present form.

At first the type locality of the Arab Formation was taken as a general area around the city of Riyadh. Extensive loss of beds and subsequent slumping along the entire outcrop prevented accurate measurement of section, however, and forced selection of a subsurface sequence to best represent the unit. Detailed correlations, carried east from the outcrop, have defined the limits of the Arab Formation in coastal wells. These limits are probably accurate within a few meters.

Because of excellent sample and core coverage, the interval from 1,371.6 to 1,499.1 m depth in Dammam well 7 (lat 26°19'04" N., long 50°07'38" E.) was chosen as the type section. The base of the Arab Formation is at the contact of clean-washed calcarenite with the tighter, more muddy rocks of the underlying Jubaila. The top of the formation falls at the change from tan sphanitic limestone below to massive anhydrite of the Hith above.

Subdivision of Arab rocks on outcrop is impossible, but in the subsurface alternating carbonate and anhydrite very naturally separate the formation into lithologically and economically significant members. In the subsurface the Arab consists of four normal marine carbonate units, each separated by thin, laterally persistent beds of anhydrite. Earlier publications (Steineke and others, 1958; Powers, 1962) informally designated the carbonate units from top to bottom as the A, B, C, and D members of the Arab Formation; the anhydrite separators were unnamed. Since the carbonates, together with their overlying anhydrite, represent four main cycles of deposition and each of these cycles approximates a time-stratigraphic unit, it now seems logical to redefine the lower three members to include their anhydrite caps (fig. 7). The much thicker upper or closing anhydrite unit (500 ft in Ghawar) is still considered a separate formation—the Hith Anhydrite.

Dammam well 7 is herewith designated as the type locality for the four members of the Arab Formation—The A Member, between 1,371.6 and 1,388.4 m depth; the B Member, between 1,388.4 and 1,399.1 m depth; the C Member, between 1,399.1 and 1,440.6 m depth; and the D Member, from 1,440.6 to 1,499.1 m depth. In each instance, the contact between members is marked by change from carbonate to evaporite.

OCCURRENCE AND THICKNESS

Rocks of the Arab Formation form a thin, essentially unbroken belt from Al Hast (lat 20°08' N.) to Juwayy (lat 25°49' N.), a distance of nearly 700 km. Width of the outcrop over this distance is relatively uniform, averaging about 10 km.

The area of Arab exposure is mainly a broad, gently undulating plain. A few low, isolated hills ("haystack jibāl") stand above the general ground level. Effects of slumping are everywhere evident—a phenomenon that can be readily attributed to the removal of anhydrite beds and the subsequent collapse of the carbonate units left behind.

No satisfactory estimate of the total thickness of the Arab has been made because of the complex slumping. Only the basal 15 to 25 m has been measured with any assurance, and even this interval con-

tains a persistent brecciated zone that suggests some loss of section due to anhydrite solution.

Between the Jubaila near Riyadh and the Hit escarpment, east of which slumping dies out, it is estimated that roughly 150 m of beds should be present. A similar estimate between Dahl Hit (lat 24°29'18" N., long 47°00'06" E.) and Al Hā'ir (lat 24°23' N.) to the west would suggest about 100 m. Obviously these estimates are of limited value, but they do serve to indicate that the Arab in this area originally had a thickness approximating that in coastal Arabia.

LITHOLOGIC CHARACTER

Lack of good Arab exposures, except for the lower 15- to 25-m interval, has prevented working out a precise lithologic sequence. The little that is known of the basic rock types indicates they are similar to those found in wells to the east. As a result, most information on the Arab has been obtained from bore holes. In fact, subsurface units, probably not differing greatly from the original outcrop sequence, have been taken as the type and reference sections.

The description of the A, B, and C Members of the Arab and the capping anhydrite of the D member in Dammam well 7 by R. A. Bramkamp and H. A. Kimball in 1955 is still the best account of the stratigraphic interval. Considerable new information has been obtained on the D Member carbonate through thin-section analysis (Powers, 1962). Consequently, the better understood sequence in Abqaiq well 71 (lat 26°18'28" N., long 49°45'45" E.) between a depth of 2,223.0 and 2,260.0 m is herewith designated as a reference section for this unit. A detailed description of the Arab Formation type-reference section is given in section 41 (p. 135).

Thicknesses of individual members change little from the coastal area toward outcrop. Each anhydrite bed does, however, thicken considerably, a change compensated for by thinning of the underlying carbonate unit. There is little doubt that, to the west, carbonate beds are progressively replaced from the top down by facies change to anhydrite. In fact, regional lithofacies studies show that maximum evaporite development, presumably mainly or entirely anhydrite, occurred along a north-south line near the longitude of Riyadh, where the amount of carbonate rocks remaining in the solution-collapse zone is small and the interval was apparently mostly soluble anhydrite.

Steineke, Bramkamp, and Sander (1958), in their concise description of Arab outcrop characteristics, point out that

only a basal unit of carbonate rocks 15-25 meters thick remains, and even within this, along nearly the entire length of its outcrop, a persistent brecciated zone suggests that at least one thin,

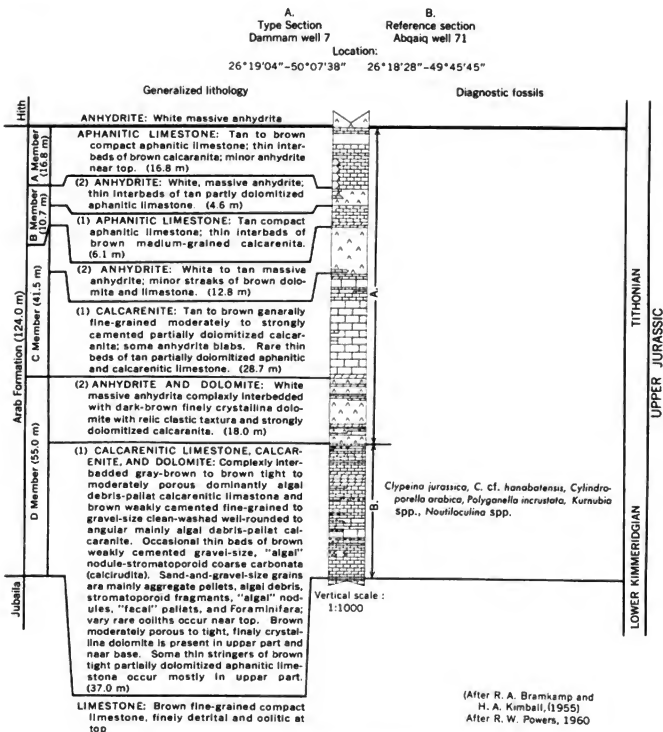


FIGURE 7.—Arab Formation type and reference sections.

highly persistent evaporite layer was included * * * Above the basal carbonate unit, little is known of the true rock sequence as good exposures are few and fragmentary because extensive solution-collapse phenomena have almost entirely eliminated outcrops of the anhydrite. * * * Dropped masses of the younger Cretaceous rocks occupy the eastern part of the solution-collapse zone, and dolomite and other carbonate rocks representing thin carbonate members, possibly equivalent to the "A," "B," or "C members" of the Arab of the Eastern Province, show at the surface in the western part.

The basal unit of carbonate rocks referred to by Steineke, Bramkamp, and Sander (1958) has been measured and studied at several localities between Al Hasi (lat 20°08' N.) and Wādī al 'Atk (near 25°30' N.). Over this entire distance there is little major variation in lithologic content except for increased dolomitization in the north and south. A section measured at Wādī Nisāb is characteristic of the interval. The lithologic sequence here is summarized in section 42 (p. 139).

There is every reason to believe that the basal Arab carbonate unit described above is equivalent to the lower part of the type D Member at Dammam; it may well represent the total D Member not replaced by anhydrite in wells as far west as Khurais and Ma' qala'.

Only at the southern end of the solution-collapse zone have beds been found in place above the basal unit. Between Sha'ib al Haddār and Al Hasi, outcrops of anhydrite rest directly on the laterally persistent calcarenite that marks the top of the basal sequence. These overlying beds have an average thickness of about 14 and are mainly white anhydrite and gypsum with thin interbeds and caps of brown dolomite. Little is known of the Arab sequence on outcrops above this stratigraphic level.

NATURE OF CONTACT WITH ADJACENT FORMATIONS

Characteristics of the Jubaila-Arab contact have already been described in connection with the Jubaila Limestone. The upper contact with the Hith Anhydrite is exposed only at a single locality—that is, in Dahl Hit (lat 24°29'18" N., long 47°00'06" E.), a solution cavity at the foot of the Hit escarpment. The contact here, as in the subsurface sequence, is at the relative sharp break from carbonate of the Arab-A Member below to massive, white, and blue-gray anhydrite of the Hith above.

Where Hith Anhydrite is preserved, as in Dahl Hit, the upper Arab contact is conformable. At all other places along outcrop, however, evaporates of the Arab-Hith sequence have been dissolved, presumably bringing residual Arab carbonate rocks into contact with slumped limestone of the Sulaiy Formation. As very thin stringers of limestone occur locally within the Hith, it is possible that some of these are present but

are as yet unrecognized on outcrop. It is unlikely, however, that any great thickness is involved. The problem is further complicated by the probable occurrence of Sulaiy rocks that dropped down and admixed with the older rocks.

Because of these complications, the surface juncture between the Arab-Hith sequence and the Sulaiy rocks cannot be precisely defined. The contact shown on the various geologic maps is only approximate.

Somewhere in the vicinity of Wādī al 'Atk, the upper surface of the Arab Formation intersects the pre-Wasia erosion surface. Although this unconformable contact cannot be traced northward, it is reasonable to assume that the Arab is progressively truncated and finally overlapped completely near Al Majma'ah (lat 25°55' N.).

PALEONTOLOGY AND AGE

The rather limited fauna so far recorded from surface exposures of the Arab Formation has not proved diagnostic. Except for *Diceras*, identifiable forms range down into the Jubaila below. Consequently, the subsurface sequence provides the only means of dating Arab rocks.

Kurnubia spp. *Nautiloculina* spp., *Clypeina jurassica* Farre, *C. cf. hanabatensis* Yabe and Toyama, *Cylindroporella arabica* Elliott, *Polygonella incrustata* Elliott and *Salpingoporella* sp. range throughout the Arab-D Member (Powers, 1962). Although some elements of this assemblage extend on into the A Member, it is only the beds of the D Member that have been reliably dated. These can be equated to at least part of Hudson and Chatton's (1959) group g beds through the No. 4 Limestone of Dukhan oil field in Qatar, the direct equivalent of the D Member of Saudi Arabia.

Hudson and Chatton (1959) also list *Calpionella alpina* Renz, *Pseudocyclammina* sp., and *Burgurdiella steineri* Hudson from group g and equivalent beds. By comparison with the Alam Abyadh limestones of southwestern Arabia, *Cidaris glandarius* beds of the Lebanon and Kurnub, and with other formations, they conclude that the faunas are Sequanian (early Kimmeridgian) in age, a dating compatible with other lines of evidence.

The post-D Member of the Arab Formation and the Hith Anhydrite have not yet been dated. However, as these beds occur between known lower Kimmeridgian and presumed Berrisian (Lower Cretaceous), it may be assumed that they are, at least in part, Tithonian.

ECONOMIC ASPECTS GROUND WATER

Many of the wells around Riyadh derive water from rocks of the Jubaila and Arab Formations, but present

data are too sparse to estimate the importance of one unit relative to the other. The general character of the Jubaila-Arab aquifer near the capital city is described more fully in connection with economic aspects of the Jubaila Limestone.

Agricultural development of the Al Kharj area, around the towns of As Sulaymāniyah and Al Yamāmah, has largely been supported by water derived from the Arab Formation. Earlier cultivation of this valley was apparently dependent on Quaternary aquifers. Three large solution pits—Samhah (lat 24°07' N., long 47°16' E.), 'Ayn ad Dil' (lat 24°07' N., long 47°16' E.), and Umm Khisah (lat 24°07' N., long 47°15' E.)—supply great quantities of water for the Al Kharj project. Samhah and 'Ayn ad Dil' have furnished most of the water in the past and will probably continue to do so. These two sinkholes, with nearly vertical sides, are situated at the toe of the low Hit escarpment. Their depth and diameter, which are essentially the same, are slightly more than 100 m. The origin of Umm Khisah is no doubt similar to the other solution cavities, although its margins are less abrupt and considerable vegetation has succeeded in getting a foothold on its banks.

Geologically, the origin of these pits is relatively simple. They occur at the toe of a badly slumped escarpment which involves mainly Sulaiy rocks but which at places also involves the lowest beds of the Yamama Formation. The slumping is reasonably regular with rocks draped down over the face of the scarp and increasing in dip to the base of the slope. On the plateau surface above, and very near the hinge line, prominent tensional cracks, some still open as far down as 10 m, indicate the mechanism by which Sulaiy beds have adjusted to the slumping. At the base of the scarp, as well as in the walls of the pits themselves, the beds are badly jumbled and brecciated. There is little doubt that the slumping has resulted from solution of supporting anhydrite layers. The Al Kharj pits fit well into this general picture and represent solution openings which succeeded in stoping their way upward to the surface.

The water-bearing member which feeds the Al Kharj pits cannot be demonstrated conclusively, although it seems likely that it is the Arab Formation. Depth of the Al Kharj pits (about 100 m) is only slightly less than the normal thickness of the Sulaiy in this region, and, as the Hith Anhydrite has been removed, the Arab can logically be considered the aquifer. In addition, there is reason to suspect that considerable filling of the pits with debris has occurred and that the actual source of the water may be somewhat deeper than their present bottoms.

A notable feature of the water is its high saturation

with calcium sulfate, a characteristic entirely consistent with its supposed origin. The chloride content of the water is low. Water levels at Samhah and 'Ayn ad Dil' rise and fall very nearly together, and it is therefore assumed that fairly efficient interconnection exists between the two pits.

Khafs Daghrāh (lat 23°50' N., long 47°12' E.), another solution pit similar to those at Al Kharj, is somewhat smaller. A less extensive agricultural development has been undertaken using water pumped from this sinkhole.

Dahl Hit (lat 24°29.4' N., long 47°00.1' E.) is also much like the Al Kharj pits in character and geologic setting except that the elevation is higher and water occurs only in the very bottom. Here again, the Arab Formation is the apparent source as the uppermost beds are exposed in the pit. In 1961 a two-stage pump was installed in the dahl. The water is now used to irrigate the alluvium-covered plain in front of the Hit escarpment.

Solution pits are also well developed in the vicinity of Laylā (near lat 22°15' N.) in Al Aḥṣā. For unknown reasons, only limited use has been made of the water. Analysis shows high calcium sulfate and low chloride-ion concentration and, here again, Arab beds are the probable source.

Quantitative estimates of Arab Formation recharge are not available; however, a great drainage area discharges across its outcrop. Since the latter is of large extent and is characterized by complicated topography there should be ample opportunity for the downward percolation of the infrequent flood waters. Large areas of closed drainage in the Arab Formation slump zone also greatly aid water to reach the main underground accumulation. Excluding the water which may be derived from areas west of Jabal Tuwayq, the watershed which is on, or must escape across, the outcrop of the Arab is of the order of 20,000 sq km. In view of this, although the amount of water entering the Arab is not known, it can be assumed to be large.

PETROLEUM

Although all members of the Arab Formation contain oil, accumulation in the upper, thinner A, B, and C carbonates is much less extensive than in the basal D Member carbonate. Oil occurs in the A and B Members of the Arab in Abu Hadriya, Dammam, Khursaniyah, Manifa, and Qatif and in minor accumulations in northern Ghawar and Abqaiq. Arab-D Member oil has been found at Abqaiq, Dammam, Fadhilli, Ghawar, Khursai, Khursaniyah, Qatif, and Abū Ṣa'fah. In all these fields, the 25- to 40-m-thick D Member as well as approximately the upper 45 m of the Jubaila Limestone are oil saturated.

Sparse information on the upper three Arab carbonate units indicates that the dominant lithology in each is admixed calcarenite and aphanitic limestone. The C Member, however, appears to have a much higher concentration of clean-washed calcarenite in comparison with the more muddy, often dolomitic rocks of the overlying A and B units. Arab-D rocks are characterized by a high percentage of lime sand, commonly skeletal and commonly in the form of massive clean-washed calcarenite beds. Calcarenitic limestone is the next most frequent rock type; pure aphanitic limestone and dolomite are quite rare. Reef structures have not yet been found, and the wide continuity, uniform thickness, and regularly bedded nature of the Arab-D suggest that large structures of this type are unlikely.

Specific particle types contributing to rock formation of the Arab-D reservoir include calcareous algae, stromatolites, and Foraminifera as the main skeletal elements and aggregate pellets, "algal" nodules, and "fecal" pellets as the most important nonskeletal grains.

The major oil deposits in the Arab-D accompany maximum development of porous calcarenite. It is certain that intergranular pore space associated with the rocks at the time of deposition almost exclusively controls present distribution of oil. To be sure, diagenetic changes including recrystallization, dolomitization, and cementation have all modified the original pore pattern to some extent, but, in each case, the effect has not been drastic.

Several of the Arab units also carry oil outside of Saudi Arabia. Most notable among these is the Dukhan oil field in Qatar which produces from limestones equivalent to the C and D Members.

HITH ANHYDRITE—UPPER JURASSIC DEFINITION

The Hith Anhydrite is named for Daħl Hit (lat 24°29'18" N., long 47°00'06" E.), a solution pit in which the type section was measured and which is still the only known outcrop.

Evolution of Hith-Arab nomenclature, from the original concept of Max Steineke in 1937 to its present form, is fully described in the definition of the Arab Formation. Both units followed the same steps from unnamed beds within the much larger Tuwaiq Formation to their modern status of separate formations.

An apparently complete Hith sequence is visible in the walls of Daħl Hit. The section here was originally measured by R. A. Brankamp and T. C. Barger in 1938 and designated the type locality. As defined by Steineke, Brankamp, and Sander (1958), the Hith is 71.2 m of bluish-gray anhydrite. The top was placed at the contact between this anhydrite and fragmental

limestone presumed to be basal Sulaiy. New well data show that the fragmental limestone is in fact collapse breccia resulting from loss of relatively thick interbeds of anhydrite. As such, it is properly part of the Hith and is so considered here, raising the total formation thickness to 90.3 m.

The top of the Hith is at the contact (possibly disconformable) of limestone breccia with evenly bedded oolite calcarenite of the overlying Sulaiy Formation. The base is taken at the sharp break from anhydrite above to calcarenitic limestone and dolomite of the Arab Formation below.

OCCURRENCE AND THICKNESS

The only definitely known exposure of the Hith Anhydrite is in Daħl Hit, a deep, steep-walled, solution cave about 32 km southeast of Riyadh. Patches of gypsum (possibly hydrated anhydrite of the Hith) occur below the Sulaiy in the vicinity of Laylā (lat 22°17' N.) and can be traced as far as lat 20°45' N. In addition, about 5 m of primary bedded anhydrite has been reported about 14 km northwest of Qasr Hīmān (lat 20°49' N.).

Except for the anhydrite at Daħl Hit, the area on outcrop where the Hith should occur is a rather broad zone of badly slumped beds. The belt of collapsed rocks can be traced over a distance of some 550 km and involves mostly Sulaiy strata. Slump effects extend beyond the edge of the Sulaiy, but this is attributed to solution of anhydrite beds within the Arab Formation. Slumping in the eastern part of the zone, on the other hand, is probably mainly due to the loss of the thicker, more massive anhydrite of the Hith itself.

Undoubtedly, the Hith is present in the subsurface over a considerable north-south distance just a few kilometers east of the solution-collapse zone. Certainly the Hit escarpment, a monoclinical flexure of Sulaiy beds between lat 23°00' N. and 25°00' N., marks the western edge of undissolved anhydrite. Drilling supports this assumption and suggests in addition that Hith beds flank the solution-collapse zone nearly throughout its length.

At the type locality the Hith Anhydrite is about 90 m thick. Elsewhere, slumping makes accurate measurement impossible.

LITHOLOGIC CHARACTER

The Hith, both at Daħl Hit and in the subsurface, is mainly massive anhydrite. Well sections usually contain some interbedded dolomite and limestone, particularly in the upper part.

R. A. Brankamp and T. C. Barger in 1938 first described the Daħl Hit section and recognized it as

the type sequence. The full exposure in the Dahl, as well as in the overlying Sulaiy cliff, was again measured in detail by S. J. Roach in 1952. His description of the succession is given in section 43 (p. 139).

So far as the Hith found in down-dip wells is concerned, a generalized section from top to bottom is as follows:

Aphanitic limestone and calcarenite of the Sulaiy Formation (Upper Jurassic? and Lower Cretaceous?)	Thickness (meters)
Hith Anhydrite:	
Anhydrite with associated limestone and dolomite	6-15
Calcarenite, limestone, and anhydrite	15-18
Largely massive anhydrite in upper part, anhydrite interbedded with aphanitic limestone, dolomite or calcarenite in lower part	90-120
Total thickness of Hith Formation	111-153
Arab Formation	

NATURE OF CONTACT WITH ADJACENT FORMATIONS

Contacts of the Hith Anhydrite with bracketing units are visible only at Dahl Ht. The lower contact with limestone of the Arab Formation (A Member) is sharp but apparently conformable. Subsurface relationships bear this out.

The highly irregular contact in Dahl Ht between massive anhydrite and limestone breccia has led some investigators to postulate a disconformity at this level—a disconformity separating the Hith and Sulaiy Formations. Extensive bore-hole data fail to confirm this concept; in fact, well sections show smooth gradation from one formation to the other as thin carbonate stringers are introduced in alternation with thicker anhydrite layers. This zone of transition now appears to correspond to the brecciated limestone interval now included at the top of the formation in Dahl Ht. It is likely that the disconformable appearance of the contact in the Dahl is due to solution effects.

PALEONTOLOGY AND AGE

The age of the Hith Anhydrite cannot be determined on direct evidence, but it obviously represents the climaxing phase of anhydrite deposition that begins in the Arab Formation (lower Kimmeridgian). As there is little likelihood of a significant stratigraphic break within the Hith-Arab sequence, at least some part of the Arab above the D Member and possibly the Hith as well must have been deposited during Late Jurassic time.

In addition, regional considerations suggest that the overlying Sulaiy Formation is of Tithonian to Berriasian(?) age. If these relationships are valid, the Hith-Arab sequence can be dated as early Kimmeridgian and Tithonian with some confidence.

ECONOMIC ASPECTS

PETROLEUM

Over much of eastern Arabia the uppermost beds of the Hith Anhydrite are commonly in porous calcarenite facies. Recently, oil was discovered in this interval in the offshore field of Manifa, and, as a result, it has been appropriately named the Manifa reservoir. Non-commercial quantities of oil were also detected in the same unit at Abu Hadriya.

As a matter of historical interest, a tar seep was discovered at Dahl Ht in 1938. The tar occurs in vugs and large pores in a 0.8-m limestone ledge at the base of the Hith. This seepage was extremely interesting as its exact position with respect to both the surface and subsurface sequence was immediately recognized. Arabian geologists realized at once the great regional significance of the discovery as it showed the probable widespread distribution of this petroliferous group of rocks, a conclusion strikingly borne out by later events.

JURASSIC AND CRETACEOUS SYSTEMS

SULAIY FORMATION—UPPER JURASSIC(?) AND LOWER CRETACEOUS(?)

DEFINITION

The Sulaiy Formation is named for Wādī as Sulayy, a gravel-filled channel at the foot of the Ht escarpment.

As originally defined by H. L. Burchfiel and K. W. Hoover in 1935, all beds between the post-Marrat and pre-Wasia unconformities were assigned to the Tuwaiq Formation. In the northern sequence studied by them, the Jubaila is the highest unit present below the Wasia.

Max Steineke in 1937, following the early definition, included in the Tuwaiq Formation a number of younger beds that underlie the "Nubian Sandstone" (that is, Biyadh plus Wasia) in the central area but that cut out to the north. The additional beds above the Jubaila were referred to simply as "Riyadh chalks and limestone, including Yamama detrital member at top."

In 1938, R. A. Bramkamp and T. C. Barger, after studying the upper part of the Tuwaiq Formation, separated out the Riyadh chalks and limestones, raised this sequence to formational rank, and defined members within it. At this stage, the Riyadh Formation included from the top down, the Yamama detrital, Sulaiy limestone, Hith Anhydrite and Lower Riyadh members.

On the discovery of what was then believed to be Lower Cretaceous fossils in the Sulaiy, the Sulaiy and Yamama detrital members were broken out of the Riyadh Formation and placed in a new formation, the Thamama. In addition to the Sulaiy and Yamama

Location:

24°29'18"—47°00'06"

Generalized lithology

Diagnostic fossils

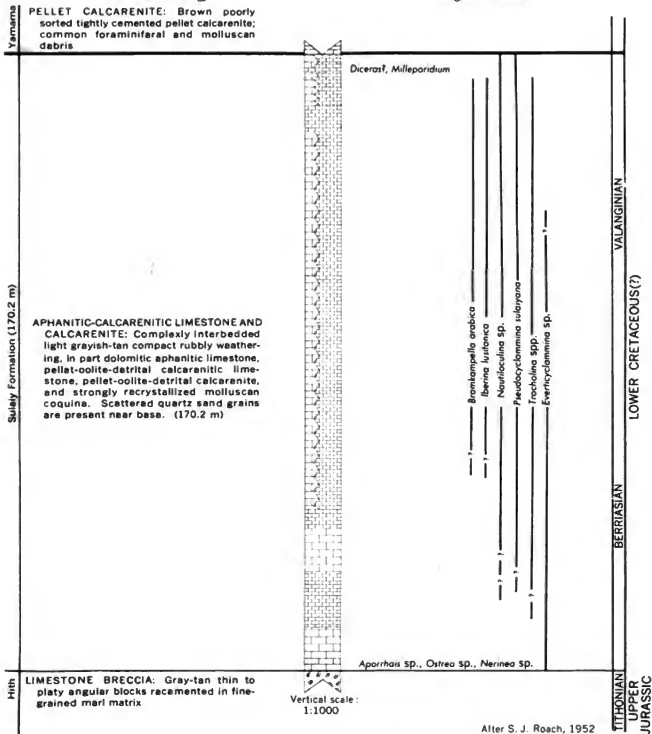


FIGURE 8.—Sulali Formation type section.

members, a group of stratigraphically higher carbonate beds was included within the Thamama formation and recognized as constituting a third, as yet unnamed member.

The first formal publication (Steineke and Bramkamp 1952b) still included these three units within the Thamama, but, by that time, the members had been formally named and raised to formational rank and the Thamama was elevated to group status. From top to bottom the three formations were designated as the Buwaib, Yamama, and Sulaiy. Later, the upper limit of the Thamama Group was redefined to include a fourth formation, the Biyadh Sandstone.

The type section of the Sulaiy Formation (fig. 8) is in the cliff above Dahl Hit at lat 24°29'18" N.; long 47°00'06" E. The upper limit is placed at the change from chalky aphanitic limestone of the Sulaiy to the more detrital calcarenitic limestone and calcarenite of the Yamama Formation. The base is at the contact of the basal calcarenite of the Sulaiy with the limestone breccia of the Hith. As pointed out in the discussion of the Hith contacts, the limestone breccia (included in the Sulaiy by Steineke and others, 1958), is now considered a part of the Hith.

OCCURRENCE AND THICKNESS

The Sulaiy crops out in a gently curving arc from lat 22°38' N. to Al Khātūlah (lat 25°26' N.). Only the Nisāh graben and a few thin banks of recent cover break the continuity of the Sulaiy over this 350 km distance. Width of the outcrop belt varies little between Khashm Khartūm (lat 23°24' N.) and Khashm al 'Ān (lat 24°44' N.).

The most prominent feature of the Sulaiy landscape is the 50- to 100-m thick, west-facing slump escarpment in the upper part of the formation. Readily recognizable for over 200 km, the escarpment (herein termed the Hit escarpment throughout its length) marks the boundary between two areas of quite different topographic expression. To the east is a gently tilted, steplike, upland surface formed by the weathering of tight, well-bedded limestone. To the west is an undulating surface of contorted limestone beds and low, complexly slumped hills. These slump features characterize lower Sulaiy outcrops even in areas where upper Sulaiy beds and the escarpment are no longer exposed—that is, generally north of Khashm al 'Ān and south of Khashm Khartūm.

A detailed analysis of the origin of the escarpment has already been presented in the discussion of the Hith Anhydrite. Suffice to say, the main cause was removal of underlying Hith evaporite by solution and subsequent draping of Sulaiy beds over the front edge of the remaining thick anhydrite sequence.

The only full measurement of the Sulaiy is at the type section where about 170 m are exposed. An Al Kharij water well, about 40 km southeast, penetrated 168 m of Sulaiy. Lack of accurate thicknesses may be attributed to several factors including: (1) the basal Sulaiy is exposed only in Dahl Hit, (2) the lower beds are complexly slumped, and (3) middle Sulaiy beds occurring at the foot of the escarpment are almost everywhere covered by recent fill.

LITHOLOGIC CHARACTER

Both surface data and near-outcrop wells show the lithology of the Sulaiy to be remarkably uniform. The main rock type is tan, chalky, massively bedded, aphanitic limestone. Some thin beds of skeletal and pellet calcarenitic limestone and calcarenite occur throughout but become particularly prominent in the lower 40 m. The basal beds also include moderate amounts of fine quartz sand.

The sequence in and above Dahl Hit was studied in 1938 by R. A. Bramkamp and T. C. Barger and was designated the type locality. About 110 m is exposed in the escarpment and approximately 60 m on the back slope.

In 1952 S. J. Roach reworked the same outcrop; his description of the sequence is given in section 44 (p. 139).

The few locations studied south of the structural complications of Wādī Nisāh show marked lithologic constancy along strike. In 1962 R. W. Powers and H. A. McClure measured the upper 44.5 m and lower 30.6 m of the Sulaiy respectively from lat 23°54'14" N., long 47°13'47" E. to lat 23°54'09" N., long 47°14'17" E. and from lat 23°46'31" N., long 47°01'22" E. to lat 23°46'16" N., long 47°01'23" E. Recent sand and gravel cover the middle part of the formation. The accessible parts of the succession are summarized in section 45 (p. 140).

NATURE OF CONTACT WITH ADJACENT FORMATIONS

The Hith-Sulaiy contact is visible only at Dahl Hit. Here, bedding planes in massive anhydrite show low angular discordance below a plane of truncation. Until recently, this discordance was cited as evidence for a disconformity at this level. Now, however, it is believed that the contact is gradational and conformable and that the angular discordance is the result of subsurface solution rather than subaerial erosion. Elsewhere, along strike, Hith strata are missing, and the Sulaiy has been down dropped against contorted Arab limestones.

From lat 23°04' N. nearly to the Darb al Hijāz (lat 24°50' N.) the Sulaiy is overlain conformably by the Yamama Formation. Throughout this distance

the contact is marked by a change from tan, chalky aphanitic limestone below to massive beds of clean-washed Yamama calcarenite above. Although the contact is covered north of the road, conformable relations between the units probably extend nearly to Al Khatilah. At about this latitude, Middle and Upper Cretaceous rocks swing across Yamama and Buwaib beds, truncate the Sulaiy, and come in contact with the underlying Arab Formation.

On the southern end of the outcrop, below lat 23°04' N., pre-Buwaib erosion cuts progressively deeper into Sulaiy strata. The formation is completely cut out near lat 22°35' N., where Buwaib rocks rest directly on Arab.

Recent sampling of the type Yamama and bracketing strata by R. W. Powers and H. A. McClure in 1962 permits accurate placement within the type sequence of faunal horizons recognized in adjacent shallow air-drilled holes. Placement of these horizons affects not only Sulaiy-Yamama-Buwaib surface correlations but sheds considerable light on their subsurface relationships as well.

C. D. Redmond also in 1962 demonstrated that the top of the Sulaiy in the area of the type Yamama should be revised upward approximately 4 m so as to include the basal member of the type Yamama. This member represents a thinned-down equivalent of the uppermost 9 to 18 m of the "Yamama detrital limestone" of deep wells. Concurrently with this the designation "Yamama detrital limestone" as used in deep-well terminology is changed to Sulaiy Formation. The advantages of these two related changes are as follows:

1. The top of the Sulaiy Formation coincides with the top of a major faunal division. *Pseudocyclammina sulaiyana* Redmond (Redmond, 1964b), which appears in the Sulaiy Formation and ranges upward to the top of the present "Yamama detrital" of the deep-well subsurface section, is thus confined to the Sulaiy Formation. The same conditions apply at outcrop where *Pseudocyclammina sulaiyana* ranges to the top of the basal member of the type Yamama, now redefined as uppermost Sulaiy.
2. In most deep-well sections, the tip of the revised Sulaiy Formation coincides with a major lithologic break accompanied by a marked electric-log signature pattern; a point corresponding to the older Sulaiy top would have to be picked on faunal evidence alone.
3. The proposed modification of existing stratigraphic terminology reconciles surface and deep-well usage. Prior to the recent findings, Lower Cretaceous stratigraphic relationships between

outcrop and subsurface were uncertain. Deep-well nomenclature, originally based on tentative comparison with the surface beds, can now be shown to be inexact and misleading. For example, "Yamama detrital" of deep wells in reality almost entirely falls within the Sulaiy of outcrop. Other correlations permit accurate subsurface definition of the Buwaib and Yamama, and these names will be carried into the subsurface as well.

PALAEONTOLOGY AND AGE

A partial list of Foraminifera occurring in the Sulaiy Formation is given below. All the forms listed range to within a few feet of the top of the formation. Their lower limits are not so clear, however, with the exception of that of the *Everticyclammina* sp., which is known to range through all but the uppermost beds of the formation.

Foraminifera of the Sulaiy Formation include: *Bramkampella arabica* Redmond (Redmond, 1964b), *Everticyclammina* sp., *Iberina lusitanica* (Egger), *Nautiloculina* sp., *Pseudocyclammina sulaiyana* Redmond, *Trocholina* sp. 1 (a large, high-spined form with a strongly protruding base and blunt apex), *Trocholina* sp. 2 (a medium-sized, low-spined form with radial fluting in the inner side of the marginal band).

Presence of a common *Nautiloculina* sp. gives the Sulaiy faunas a Jurassic aspect although this genus is known to extend into the Lower Cretaceous.

Recent work by Maync (1959) has demonstrated that *Iberina lusitanica* has a somewhat extended vertical range, first appearing in the lower Kimmeridgian and extending upward across the Jurassic-Lower Cretaceous boundary into the lower Valanginian. Its presence in the Sulaiy Formation of Saudi Arabia is helpful only insofar as it limits the possibilities for age assignment to either Late Jurassic or earliest Cretaceous.

Pseudocyclammina sulaiyana Redmond was discussed and figured by Henson (1948) as *Pseudocyclammina* aff. *litus* (Yokoyama) from Qatar Dukhan well 2, presumably in beds equivalent to the Sulaiy Formation. Henson listed a stromatoporoid, *Cladocoropsis* sp., as occurring at the same level and considered the age of the beds to be Late Jurassic.

Until such time as more definite evidence is obtained it seems best to leave the age assignment of the Sulaiy Formation open, listing it as Tithonian to early Valanginian.

A comprehensive list of fossils found in the Sulaiy Formation includes: *Chaetetes* sp., *Milleporidium* sp., *Aporrhais* sp., *Diceras*? sp., *Exogyra couloni* d'Orbigny, *Nerinea* aff. *N. blancheti* Pictet and Campiche, *Nerinea* sp., *Ostrea* sp., and miscellaneous cidaroid radiolites.

ECONOMIC ASPECTS

GROUND WATER

Because of their generally aphanitic and tight character, Sulaiy rocks appear unfavorable as water reservoirs. This impermeability does serve a useful purpose, however, in that water falling on the back slope of the Hit escarpment drains into and recharges both the Wādī Nisāb-Wādī as Sahbā' channel system and the Biyadh-Wasia sandstone aquifer.

PETROLEUM

Porous Sulaiy rocks contain oil in one Saudi Arabian field—that is, the offshore field of Manifa. Here, the producing interval or Lower Ratawi reservoir is about 250 ft of calcarenite and calcarenitic limestone. As is true of most Arabian carbonate reservoirs, oil accumulation is directly related to development of clean-washed lime sand (calcarenite). Other Middle East fields outside of Saudi Arabia also presumably have discovered productive oil in the Sulaiy.

CRETACEOUS SYSTEM

YAMAMA FORMATION—LOWER CRETACEOUS

DEFINITION

The Yamama Formation is named for the town of Al Yamamah (lat 24°11' N.) about 20 km north of the type section and on line with the strike of outcrop. Development of Yamama nomenclature from an unnamed part of the Tuwaiq Formation to a formation within the Thamama Group is described in detail in the definition of the Sulaiy Formation.

The Yamama type section was pieced together from a number of short exposures on the Al' Qusay's' upland surface between lat 24°00'24" N., long 47°15'42" E. and lat 24°00'24" N., long 47°20'54" E.

As defined by Steineke, Brankamp, and Sander (1958), 58 m of section between the dense Sulaiy limestone below and pre-Buwaib unconformity above was assigned to the type Yamama. As already mentioned in connection with the Sulaiy, recent work has shown that the basal 4 m of the Yamama type sequence belongs logically with the Sulaiy. The lower limit of the Yamama is herewith redefined to account for this change.

The picture is further complicated by the fact that many beds assigned to the lower part of Buwaib at its type locality further north were also included in the Yamama type sequence. In addition, it is certain that the "pre-Buwaib unconformity" was somewhat misplaced in both areas. To straighten out the relationships between the Yamama- and Buwaib-type sequences and adhere as far as is feasible to older concepts, the upper limit of the Yamama has been adjusted in the outcrop and subsurface to coincide

with the now accurately placed "pre-Buwaib" surface of unconformity. At the Yamama type locality this involves lowering the Yamama-Buwaib contact about 8 m. The effect on the Buwaib-type sequence has been to include the lower 23 m in the Yamama and restrict the Buwaib to approximately the upper 10 m. Evidence for these changes is as follows:

1. Analysis of the type Buwaib microfossils by means of recently developed species keys shows that *Cyclammina greigi* sensu stricto does not range below the top 10 to 12 m of the formation. Also, forms which appear in samples immediately below that level are those which are known elsewhere only from the Yamama Formation. Furthermore, the echinoids from the type Buwaib are associated with these lower forms and appear to fall below the lower limit of *Cyclammina greigi*.
2. Specimens of *Pygurus* cf. *P. rostratus* from the type Buwaib came from a position high in the formation as originally defined. This species can now be accurately placed within the type Yamama microfaunal sequence and can be demonstrated to fall below the range of *Cyclammina greigi* here as well.

There is no possible doubt that at least the lower 23 m of the type Buwaib is equivalent to a roughly comparable interval in the lower part of the type Yamama and that the echinoid occurrences in the two areas fall very nearly at the same level in time.

Redefinition of the Yamama now places 45.5 m of strata in this unit at the type locality. The base is at the contact of chalky aphanitic and calcarenitic limestone of the Sulaiy below with golden-brown calcarenite of the Yamama above. The top is placed at the unconformable break from golden-brown pelletal calcarenite below to molluscan calcirudite of the Buwaib above.

OCCURRENCE AND THICKNESS

Outcrops of the Yamama form a very thin, curved band from lat 23°04' N. to the northern end of Jāl Buwayb (lat 25°24' N.), a distance of nearly 300 km. In the central area the band reaches a maximum width of about 9 km. Yamama rocks are continuously exposed from their southern limit to Wādī Nisāb where the beds are covered by younger deposits. The formation reappears north of the wādī, then persists to the northern edge of the Al Jubayl plateau where it passes under Quaternary cover. It is again exposed for about 25 km at Jāl Buwayb in the steep face of the Al 'Aramah escarpment.

Except for the clifflike exposures at Jāl Buwayb, Yamama rocks usually weather to a gently tilted, steplike series of dip slopes and low parallel benches

or hills. These are in turn superimposed on the flat upland surface dipping east from the Hft escarpment.

Complete measurement of the Yamama sequence has been made at two localities. At the reference section (near lat 24°00' N.) the formation is about 45 m thick; far to the north near Khashm Buwayb (lat 25°15' N.) it is about 25 m thick. Intraformational correlations show that most of the loss of section north from the reference area is due to pre-Buwaib truncation.

About 10 km south of the reference section (near lat 23°54' N.) another full Yamama sequence (40 m) can be pieced together from a measured section and two shallow air-drilled holes. As these holes were spudded directly on the outcrop, their stratigraphic position in terms of the surface sequence is precisely known. At this locality, loss of beds relative to the reference section can be attributed to pre-Buwaib erosion. Beveling of the Yamama continues southward nearly to lat 23°00' N. where the entire unit is eliminated.

LITHOLOGICAL CHARACTER

Basically the Yamama Formation, like the Sulaiy, is a nearly pure carbonate unit. Calcarene, calcarenitic limestone, and aphanitic limestone occur in varying proportions along strike. Clean-washed calcarenite and calcirudite are the main rock types at the type locality; away from this area progressively muddier sediments—aphanitic and calcarenitic limestone and even very thin layers of shale—come in.

R. W. Powers and H. A. McClure in 1962 measured in detail a full Yamama sequence not far from where R. A. Bramkamp originally pieced together the type section. Samples collected at closely spaced intervals along the traverse provide the most complete record of Yamama outcrop lithology now available. As a result, the section is herewith designated a reference locality.

The reference section (fig. 9) is a composite of three isolated but overlapping measurements. The lower 26.5 m was measured along the back slope of the Hft escarpment between lat 24°00'37" N., long 47°15'40" E. and lat 24°00'13" N., long 47°16'54" E. Another 11 m was picked up in the side of a low hill from lat 24°01'04" N., long 47°19'01" E. to lat 24°00'48" N., long 47°19'08" E. The upper 8 m was described at another hill between lat 24°02'47" N., long 47°20'20" E. and lat 24°02'42" N., long 47°20'27" E.

Rocks found in the reference section are typical of Yamama exposures elsewhere; hence, a complete description is given in section 46 (p. 140).

NATURE OF CONTACT WITH ADJACENT FORMATIONS

The Yamama Formation rests conformably on the

Sulaiy, and thus, throughout the length of outcrop, limestone lies on limestone. Generally, however, the break is marked by a change from tan, moderately porous aphanitic limestone below to brown, tightly cemented pellet calcarenite above. In addition, Sulaiy bedding tends to be thicker and more resistant to erosion, and, on weathering, these beds form a steplike series of 2- to 10-m sheer cliffs separated by short intervals of dip slope. In the Yamama, on the other hand, short intervals of soft beds form low-angle slopes each capped by a thin 0.5- to 2.0-m resistant ledge.

The contact between the Yamama and overlying Buwaib Formation is unconformable. In spite of this, the break—limestone on limestone—is inconspicuous, and exact placement must often await detailed faunal control. Beveling of the Yamama involves only a few meters per kilometer, and the unconformity can only be recognized by the systematic disappearance of units over a long distance. For example, from the reference section south, the Buwaib rests on progressively older units of the Yamama, cuts across the Sulaiy, and then rests on Arab beds.

Although some pre-Buwaib truncation of the Yamama is apparent north of the reference section, surficial deposits cover the units before the Yamama is fully cut out. In fact, it is quite possible that some lower Yamama strata persist beneath the cover far enough north to intersect the pre-Wasia unconformity near Wādī al 'Atk.

PALEONTOLOGY AND AGE

Occurrences of *Pygurus rostratus* Agassiz and *Trematopygus* cf. *T. grasi* d'Orbigny (identified by J. Roger fide Sander in Steineke, Bramkamp, and Sander, (1958) within the Yamama Formation are indicative of a Valanginian age.

A partial list of Foraminifera from the Yamama Formation is as follows: *Everticyclammina eccentrica* Redmond, *Everticyclammina elegans* Redmond, *Pseudocyclammina cylindrica* Redmond (Redmond, 1964b), *Pseudocyclammina* spp., *Trocholina* sp. (a large, low-spired form with the base more convex than the spiral side). As nothing is known of the occurrence of the above Foraminifera outside of Saudi Arabia, they can have no special significance, in themselves, in determining the age of the formation.

A comprehensive list of Yamama fossils includes: *Astrocaenia*? sp., *Milleporidium* cf. sp., *Pygurus rostratus* Agassiz, *Trematopygus* cf. *T. grasi* d'Orbigny, cidaroid radiolites, *Cyclammina* spp., *Everticyclammina eccentrica* Redmond, *Everticyclammina elegans* Redmond, *Pseudocyclammina cylindrica* Redmond, *Pseudocyclammina* sp., *Trocholina* spp., *Haplophragmium* sp., *Haplophragmoides* sp., *Trochammina* sp., *Anis-*

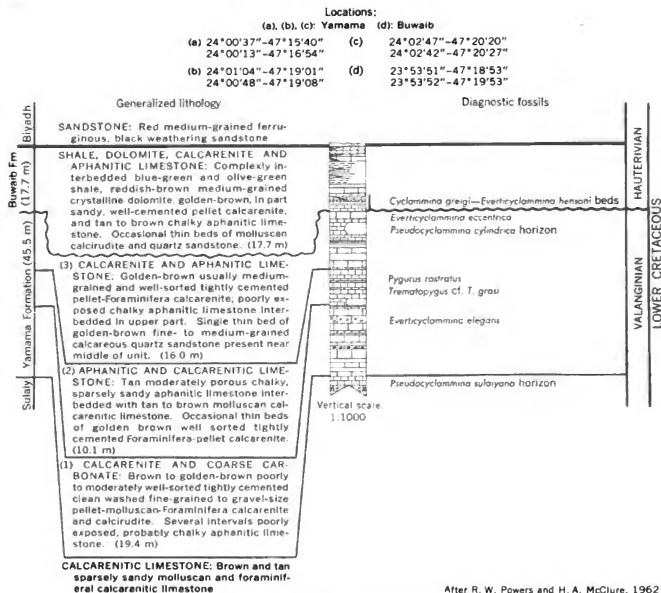


FIGURE 9.—Buwaib and Yamama Formations reference sections.

cardia sp., *Aporrhais* sp., *Cerithium* (s.l.) sp., *Corbis* sp., *Corbula* sp., *Chione* cf. sp., *Cuculaea*? sp., *Exogyra* sp., *Gyrodes*? sp., *Gryphaea balli* (Stefanini), *Homomya* sp., *Lima* sp., *Modiolus*?, *Natica* sp., *Nuculana* sp., *Ostrea* sp., *Paphia* sp., *Pholadomya* cf. *P. decusata*, *Pleurotomaria*? sp., *Siliqua* sp., *Straparolus*? sp., *Tellina* sp., *Trigonia* sp., *Trochus* sp., *Venus* sp., unidentified ammonite genus showing affinities with *Knemidoceras* and *Hypenoceras*, and unidentified small molluscs.

ECONOMIC ASPECTS

The offshore field of Manifa contains productive oil in the Yamama Formation (Upper Ratawi reservoir).

This is the only occurrence in this formation within Saudi Arabia, but other Middle East fields presumably have accumulations at this level as well. At Manifa, the effective thickness is small and limited to calcarenite development in a dominantly aphanitic interval.

BUWAIB FORMATION—LOWER CRETACEOUS

DEFINITION

The Buwaib Formation is named for Khashm Buwayb (lat 25°15' N.) near where the type section was measured. Development of Thamama Group (including Buwaib Formation) nomenclature from its

inception to modern usage is covered in detail under the definition of the Sulaj Formation (p. 66).

Recent work has shown that some modification of the type Buwaib as defined by Steineke, Brankamp, and Sander (1958) is necessary. It can now be demonstrated that the lower two-thirds of the 33.8-m interval previously assigned to the type Buwaib is, in fact, equivalent to the lower part of the type Yamama and, in addition, falls below the pre-Buwaib unconformity. Supporting evidence has already been cited as part of the discussion on the Yamama Formation (p. 70).

Based on the new data, it now seems logical to restrict the name Buwaib Formation to the upper 11.2 m of the type section at Khashm Buwayb and throw the lower 22.6 m with the Yamama. Thus, the Buwaib would take in all beds carrying *Cyclammina greigi* and would put the base of the formation at the stratigraphic break that elsewhere has been called the "pre-Buwaib unconformity" in both surface and subsurface reports.

The section measured in the face of Jāl Buwayb at lat 25°15'03" N., long 46°38'52" E. is held as the type locality for the Buwaib (restricted). The base is at the unconformable contact of cream-colored aphanitic limestone above with quartzose sandstone and aphanitic limestone of the Yamama below. The top is at the highest limestone below the sandstone of the overlying Biyadh.

OCCURRENCE AND THICKNESS

Outcrops of the Buwaib Formation have been mapped in a narrow irregular band from Khashm al Bāzūm (lat 20°38' N.) to the northern end of Jāl Buwayb (lat 25°24' N.), a distance of nearly 600 km. South of Khashm al Khufaysah (near lat 23°00' N.) average width of the outcrop is about 18 km; to the north, it is about 2 km.

Continuity of the Buwaib is broken at several places—notably, at Al Afāj (lat 22°10' N.) where a 50 km wide sheet of gravel cuts through the Lower Cretaceous, again at Wādī Nisāb where the central Arabian graben system funnels through, and finally just north of lat 25°00' N. where exposures are covered for 30 km by surficial deposits.

In addition to the main belt of outcrop, several small outliers of Buwaib are preserved in the slumped and brecciated zone just west of the Hīt escarpment. The most prominent of these occur in front of Khashm Khariūm (lat 23°23' N.) and Khashm Fazrā' (lat 23°38' N.) and west of 'Irq Banbān (in the vicinity of lat 25°00' N.). Certainly Buwaib rocks are down dropped in other areas as well, but structural complications and lithologic similarity have so far prevented accurate sorting of the various units involved.

Except for the steep cliff face at Jāl Buwayb, the

unit weathers to a relatively low-relief plain. The generally flat surface is broken, however, by several small discontinuous benches that crop out at various levels through the section.

In the southern area of outcrop—generally between Wādī ad Dawāsir and Wādī Birk—Buwaib Formation thickness is relatively constant at 40 to 45 m. There is considerably more fluctuation in sections measured to the north—for example, 18 m at the reference section (lat 23°54' N.), 33 m near lat 24°00' N., about 20 m near the Darb al Hijāz (lat 24°52' N.), and 11 m at the type section near Khashm Buwayb (lat 25°15' N.).

LITHOLOGIC CHARACTER

Although the Buwaib contains several rock types, the general lithologic character changes but little along strike. Aphanitic limestone and calcarenitic limestone are most common, but invariably the sequence is broken with thin intervals of calcarenite, sandstone, and shale. Beds of clean quartzose sandstone appear to be confined to the upper part of the formation.

One of the most complete sections of the Buwaib so far studied is a few kilometers northeast of Khafṣ Daghrah (lat 23°50' N.). Here R. W. Powers and H. A. McClure in 1962 measured and sampled the entire sequence which is herewith designated as a reference section (fig. 9). The formation was studied on a continuous traverse from lat 23°53'51" N., long 47°18'53" E. to lat 23°53'52" N., long 47°19'53" E. A full description is given in section 47 (p. 141).

Sections at the extreme northern and southern ends of the outcrop belt fail to show any significant differences in the lithologic pattern seen at the reference locality. For example, the type sequence at Khashm Buwayb may be summarized as follows: At the base 3.8 m of aphanitic limestone with thin interbeds of calcarenitic limestone and calcarenite, overlain in turn by 1.7 m of friable sandstone, 3.7 m unexposed but probably shale, and 2.0 m of thinly interbedded sandstone and sandy calcarenitic limestone.

Southerly exposures are characterized by a section just north of Qasr Hīmān (lat 20°49' N.). The sequence here may be summarized as given in section 48 (p. 142).

NATURE OF CONTACT WITH ADJACENT FORMATIONS

The Buwaib Formation rests unconformably on all underlying units with which it comes in contact. From the vicinity of Jāl Buwayb nearly to lat 23°00' N., the Buwaib rests on different beds of the Yamama Formation. Southward, the Buwaib progressively overlies the Sulaj and finally comes in contact with Arab strata about 20 km north of Laylā.

The upper contact with the Biyadh Sandstone is everywhere conformable and gradational. It is expressed as a low discontinuous bench of Buwaib limestone capped by a thin veneer of reddish-black, ferruginous sandstone of the Biyadh.

At the southern end of the outcrop, the Buwaib disappears under gravels dispersed by the Wādī ad Dawāsīr drainage system, and its ultimate limit is unknown. Surficial cover also obscures events on the northern end of the outcrop belt beyond Jāl Buwayb. In this place, however, regional geometry suggests that the Buwaib persists to Wādī al 'Atk and is there truncated by pre-Buwaib erosion.

PALaeONTOLOGY AND AGE

Surface exposures of the Buwaib Formation carry *Cyclammina greigi* Henson, *Eertercyclammina hensoni* Redmond, and several other litulids.

As the Buwaib unconformably overlies the Valanginian Yamama Formation along the outcrop and underlies the lowermost occurrences of *Orbitolina* cf. *O. discoidea* Gras, *O. discoidea* Gras var. *delicata* Henson, and *Choffatella decipiens* Schlumberger in subsurface, its position would be within the Hauterivian.

Buwaib fossils include: *Ammobaculites?* sp., *Cyclammina greigi* Henson, *Eertercyclammina hensoni* Redmond, unidentified litulids, and unidentified small molluscs.

BIYADH SANDSTONE—LOWER CRETACEOUS

DEFINITION

The Biyadh Sandstone is named for Al Biyāḍ, an extensive gravel-covered plain that marks the area of outcrop. Beds now assigned to the Biyadh were first included by T. W. Koch and C. W. Brown in 1934 as part of a larger unnamed clastic series of presumed Cretaceous age. H. L. Burchfiel and J. W. Hoover applied the name "Nubian Sandstone" to this unit in 1935 because of similarity to the Cretaceous section in Lebanon.

Max Steineke in 1938 pointed out that the Nubian Sandstone is primarily a facies term with no stratigraphic significance. It had been used in Egypt, Sinai, Lebanon, and Palestine as a "catch-all" for arenaceous sediments of widely differing ages. The Arabian sandstone, on the other hand, occupied a definite stratigraphic position and could only be correlative with the upper part of the succession in Egypt. For that reason, the loose term Nubian Sandstone was replaced by the name Wasia Formation. The Wasia was bracketed at the top by limestone of the Aruma Formation and at the base by limestone that is now Buwaib. The Wasia as thus defined

appeared in publication in 1952 (Steineke and Bramkamp, 1952b).

Truncation and overlap within the Wasia as first defined had long been recognized. The exact surface of unconformity, however, was only recently pinpointed by detailed field and aerial photomapping. With these data, it could be demonstrated that the Wasia contained two sand units separated by a major unconformity. Consequently, in 1952 Bramkamp tentatively removed the beds below the unconformity from the Wasia and assigned them to a new formation—the Biyadh Sandstone. The Biyadh, because of its considered Lower Cretaceous or Neocomian age, was and still is the upper formation of the Thamama Group. Concurrently, the beds remaining above the unconformity were assigned to the Wasia (restricted). The new terminology first appeared in a paper by Thralls and Hasson (1956), and formal publication of stratigraphic limits followed in 1958 (Steineke and others).

The definition of the Biyadh and Wasia Formations noted by Steineke, Bramkamp, and Sander (1958) has been retained in this paper. There is considerable evidence, however, that the Biyadh-Wasia boundary on outcrop does not coincide stratigraphically with the subsurface contact. In fact, there seems little doubt that strata assigned to the upper Biyadh at the surface are included within the Wasia in deep-well sections (fig. 1). At least one and possibly several unconformities, obscured by sand-on-sand relationship, complicate the picture.

The Biyadh section was measured along a two-part traverse: (pl. 9) (1) the lower part from the base of the sandstone at lat 24°06'38" N., long 47°23'53" E. (near Ath Thulaymā') east to lat 24°05'28" N., long 47°38'07" E. and (2) the upper part from a point at lat 24°00'03" N., long 47°35'09" E. (the same stratigraphic level as the top of unit 1) southeast to lat 23°58'38" N., long 47°41'37" E. Recalculations based on new dip data show the Biyadh at the type locality to be about 425 m thick.

The base of the Biyadh is at the top of the highest thin marine limestone beds of the Buwaib Formation. The top is at the unconformable contact of coarse quartz sand with quartz pebbles and the overlying ferruginous silty sandstone of the Wasia Formation.

OCCURRENCE AND THICKNESS

Sandstone of the Biyadh can be traced almost continuously from Wādī ad Dawāsīr to Wādī al 'Atk, a distance of nearly 650 km. Only two breaks of any significance occur, and these are the synclinal area of Wādī as Sahbā' where Wasia and Aruma sedimentary rocks effectively mask the Biyadh and the gravel sheet at Al Aflāj (about lat 22°10' N.). Nearly 50 km wide

at Wādī ad Dawāsir, the Biyadh narrows persistently northward to Khashm Khanfir al Khafs (lat 25°35' N.) where it pinches out in the face of the Al 'Aramah escarpment. Southward, the Biyadh disappears beneath alluvial gravel and eolian sand of the Rub' al Khālī. Scattered exposures of combined Biyadh and Wasia are known within the sand-covered area; the most prominent are at Al Jaladah (near lat 18°30' N.) and Ash Sharawrah (near lat 17°15' N.).

From Wādī as Sahbā' south, weathering of the Biyadh results in a characteristic landscape made up of numerous small dark-colored to black hills between which are gently rolling white, gravel-covered plains. The Arabs refer to this belt as Al Biyād which roughly translated means "the white country." The same general topography picks up again north of Wādī as Sahbā', but here the terrain is somewhat rougher and more difficult to traverse.

Gravel littering the Biyadh surface is apparently residual and is composed almost wholly of white, well-rounded quartz pebbles and lesser amounts of quartzite and fossil wood. Some igneous and metamorphic grains also occur, but these are generally concentrated near major channels that originate west of Jabal Tuwayq, breach this barrier, and extend across Lower Cretaceous units.

The maximum thickness of the Biyadh so far calculated is 625 m in the vicinity of Banī Labab (lat 20° 42' N.). Northward, definite though irregular thinning takes place. Intervals of 515, 510, 425, and 360 m were computed respectively near Wādī al Maqran (lat 21°20' N.), Wādī Birk, the type locality, and latitude 24°40' N. Beyond, pre-Wasia truncation is rapid and the formation wedges out completely within about 140 km.

Bore holes in the southwest Rub' al Khālī penetrated Biyadh sections which, although incomplete, give some idea of formation thicknesses in this area. About 490 m was recorded at Al Jaladah and some 375 m is present at Ash Sharawrah.

LITHOLOGIC CHARACTER

The lower three-fourths of the Biyadh is mostly light-colored, often black-weathering and crossbedded quartz-sandstone with some interbeds of varicolored shale. Conglomeratic layers and thin beds of ironstone occur at several levels. From the area of Wādī as Sahbā' north, this lower sequence is capped by a prominent 10-m interval of complexly interbedded marl, limestone, shale, sandstone, and reddish-brown siderite-dolomite.

Above the calcareous unit the remainder of the Biyadh is coarse-grained, crossbedded quartz sandstone containing abundant quartz pebbles. This conspicuous band of gravels is known informally as the "Biyadh

Gravel Stripe." It is distinct both on the ground and aerial photographs and can be traced south for several hundred kilometers, even far beyond where the underlying calcareous member gives out. The upper limit of this white gravel stripe is taken as the Biyadh-Wasia contact.

The bulk of the Biyadh appears to be of nonmarine origin, except for the thin carbonate stringer which contains poorly preserved marine molluscs and a poorly preserved nondiagnostic marine microfauna found 25 to 30 m below the carbonate stringer. C. D. Redmond in 1962 suggested that the lower marine lithology may represent a western extension of the environment recognized in the subsurface as the Maaddud Limestone Member of the Wasia Formation. Unfortunately, proof is lacking; if this could be demonstrated, much of the uncertainty regarding Biyadh-Wasia surface-subsurface relationships would be eliminated.

The type section of the Biyadh is considered to be that measured about 20 km south of Wādī as Sahbā' by D. A. Holm and N. M. Layne in 1949. Their description of the rocks exposed (section 49, p. 142) at this locality serves as an excellent summary of Biyadh rocks all along the outcrop belt.

NATURE OF CONTACT WITH ADJACENT FORMATION

The contact with the underlying Buwaib is conformable and gradational and is placed at the top of the highest limestone bed of the Buwaib. Throughout the outcrop area this consistent horizon follows the top of a half-meter bed of reddish limestone or dolomite. Immediately above is the typical ferruginous black-weathering sandstone of the Biyadh.

The Biyadh Sandstone is unconformably overlain by the Wasia. The contact is marked by a change from coarse quartz sandstone with abundant pebbles to ferruginous silty sandstone of the basal Wasia. A marked color change occurs at the break. Below is the laterally persistent white "Biyadh Gravel Stripe"; above is the varicolored siltstone, sandstone, and shale of the Wasia.

PALEONTOLOGY AND AGE

There is considerable uncertainty regarding the exact stages represented by the Biyadh surface sequence as now defined. Definite outside limits are known, however, as the underlying Buwaib is definitely Hauterivian and the overlying Wasia is confidently dated on ammonites as Cenomanian.

Some help comes from the subsurface where the "Biyadh" is bracketed by Buwaib (Hauterivian) below and Shu'aiba (Aptian) above. *Choffatella decipiens* Schlumberger, *Dictyoconus arabicus* Henson, and *Orbitolina discoidea* Gras are limited to the Biyadh;

the presence of any one of these species is sufficient to indicate a position within the formation. Based on contained forms and regional considerations, the subsurface Biyadh is probably Barremian and lower Aptian. As presently interpreted, these beds would equate approximately to the lower 200 to 250 m of Biyadh at the type locality.

In connection with this, there is some suggestion that the interval from about 275 to 325 m above the base of the type Biyadh may be of late Albian to early Cenomanian age. Several species of *Ammobaculites* of the type generally associated with brackish-water deposits were discovered when this interval was penetrated by shallow air-drill holes. None of the distinctive genera and species that usually distinguish the Wasia in deep wells are present here, and possible comparison of these beds with parts of the subsurface Wasia can be justified only on two lines of indirect evidence. The first of these is lithologic. In general, and particularly toward the west, the Wasia is characterized by ferruginous elements such as siderite, concentrically layered ferruginous pellets, and ironstone concretions as well as ferruginous shales. The correlation point based on the occurrence of *Ammobaculites* falls within the lower part of a series of beds manifesting just such a lithology. The other point of indirect evidence lies in the fact that toward the west both the Wasia and Biyadh beds tend to become less and less marine, to the point where only marine microfossils are found at the level of the basal Ahmadi Member (lower Cenomanian) of the Wasia and, more sparingly, in beds immediately underlying the Maaddud Limestone Member (lowermost Cenomanian). Bearing this in mind, it is possible to theorize that the *Ammobaculites* and zone of marine molluscs just above represent the westerly extension of this marine environment.

It is possible that the Biyadh as now defined on outcrop could include beds ranging in age from Hauterivian or Barremian to Cenomanian. Such age assignment would be in sharp conflict with the much better known subsurface sequence where upper Aptian to Turonian strata are included within the Wasia. Unfortunately, however, east-to-west gradation from marine shale and limestone to nonmarine sand and gravel is accompanied by facies changes of such magnitude and rapidity that it has proved impossible to recognize any widespread marker horizons. Because of this, there is little likelihood that the Biyadh-Wasia contact in the subsurface can ever be placed with certainty in terms of the surface sequence, and vice versa. The widespread usage, ease of recognition, and economic importance of the subsurface division throughout the Persian Gulf area

makes it seem most logical to carry the Biyadh as Barremian and lower Aptian. Clearly, this dating may not involve the upper 200 m of the type section.

ECONOMIC ASPECTS

GROUND WATER

In the outcrop area the Biyadh and Wasia sands, and to a small degree Quaternary alluvium, constitute a single intake area and hydraulic unit. A short distance down dip, fluid communication between the Wasia and Biyadh is restricted, and each operates as an isolated hydrogeologic system.

Recharge occurs primarily from precipitation by means of direct percolation into the intake area and channel subsurface inflow from the runoff area. The major channels that drain the runoff area act as a recharge mechanism throughout the year.

Three basic types of water are recognized: (1) Fresh meteoric, (2) mixture of fresh meteoric and connate, and (3) near-connate. The fresh meteoric waters contain as much as about 4,000 ppm (parts per million) of total solids and occur largely in the west toward outcrop. Mixed water, which ranges from about 4,000 to 35,000 ppm of total solids, results from incomplete flushing of connate water and occurs generally east of the meteoric belt. The connate water contains about 35,000 ppm of total solids and is known only at a few isolated localities within the mixed-water belt. Presumably these areas are residual original water somehow bypassed and undiluted by newer meteoric recharge.

Nonpotable Biyadh water is being injected into the oil reservoir at the Ain Dar area. Biyadh water is also used for irrigation only at Al Bijādiyyah, an agricultural development in Wādī as Sahbā' generally across the Biyadh-Wasia outcrop belt. A total of 54 nonartesian wells have been drilled. Except for three wells completed in Quaternary gravel to the west, all the wells are completed in the Biyadh-Wasia sands. The number of permanent pump installations is uncertain; probably less than 30 have been made.

The Al Bijādiyyah area is underlain by 300 m of highly productive water-saturated sediment that is constantly recharged by fresh meteoric water slowly seeping downward through channel fill. To the west, on the south side of Wādī as Sahbā' where the water table rises above the base of the Quaternary alluvium, the shallow, subsurface, highly permeable gravel channel(s) which act as conduits for movement of water down the wādī, can be developed as well.

PETROLEUM

The main economic interest of the Biyadh is its equivalence to the Zubair zone which is productive in

southeastern Iraq. Within Saudi Arabia proper, the only significant show of Biyadh-Zubair oil is a minor accumulation in Safaniya.

WASIA FORMATION—MIDDLE CRETACEOUS

DEFINITION

The Wasia Formation is named for Khashm Wasi' (lat 24°23' N.), where a complete section is exposed. Changes leading to the present definition of the Wasia have been discussed in connection with the Biyadh Sandstone (p. 74).

Stratigraphic details of the Wasia as now defined were first published by Steineke, Bramkamp, and Sander (1958). The type section is in the lower slope of Al 'Aramah escarpment, extending from the pre-Wasia unconformity (at lat 24°23'04" N., long 47°45'12" E.) southeast to low hills near Wasi' (lat 24°22'38" N., long 47°45'49" E.). The base is at the contact of varicolored fine-grained sandstone and siltstone of the Wasia with underlying light-colored, pebbly, coarse-grained sandstone of the Biyadh. The top is at the disconformable contact of Wasia sandstone with dolomite and limestone of the Aruma Formation above.

Relationship of the Wasia to a thick elastic unit in northwestern Arabia—the Sakaka Sandstone—has long been controversial. Various dates as upper Paleozoic and Middle Cretaceous, the only rigid limits were imposed by the underlying Lower Devonian Jauf Formation and overlying Upper Cretaceous Aruma beds. Recently drilled bore holes have, however, now bridged the gap between the two units and extended the Wasia northward to where there is little doubt that it is laterally continuous with the Sakaka. Hence, the Sakaka is herein described simply as a prolongation of the Wasia. The term Sakaka, first applied by R. M. Sandford in 1950 to cover the doubtful unit, is herewith considered obsolete.

OCCURRENCE AND THICKNESS

The southernmost occurrence of definite Wasia is near Wadi Dawasir. From here, the formation continues northward in a great arc to where it passes under the western edge of An Nafud (near lat 28°25' N.). The unit again emerges around Sakakah (lat 30°00' N.) where it has been mapped as the Sakaka Sandstone. Total linear distance of Wasia exposure to this point is nearly 1,450 km. A number of small outliers also occur west and southwest of Sakakah, for example: (1) In hills which stand up along the north side of the At Tawil fault (near lat 29°22' N.), (2) on the tops of hills rising above Al Huj plateau, and (3) around Umm Nukhaylah (lat 29°30' N., long 38°33' E.) where

the sandstone is preserved in structurally disturbed blocks.

From An Nafud to Ar Rub' al Khali the Wasia is interrupted only by such through-cutting channels as Al Ba'in, Wadi al 'Atk and Wadi as Sahba'. Patches of sandstone bedrock cropping out in windows in the Rub' al Khali sand mantle have been described as Biyadh and Wasia undivided; Al Jaladah and Ash Sharawah are exposures of this type. Actually, however, there is some doubt that the Wasia extends that far southwest.

The strike of Wasia beds changes sharply in two places—that is, Wadi as Sahba' and Wadi al 'Atk. In each case Wasia exposures turn almost due west, and the wadis cut abruptly down through the section. Presumably in both cases structural happenings, possibly also related to wadi formation, are responsible.

In the central and northern areas of outcrop, Wasia beds typically weather to an upward-steepening slope that terminates in an almost sheer face beneath the scarp-forming limestone of the Aruma Formation. In the southern area, beginning about 40 km south of Wadi as Sahba', the Aruma progressively loses its cliff-forming ability as the formation is replaced from the bottom up by softer sandstone. Complete replacement is effected near lat 22°30' N., and, with this change, the surface of the Aruma and Wasia breaks down to about the same general level as the adjacent Biyadh plain.

Near Sakakah, the formation crops out as a rough, maturely dissected plateau with scattered hills that follow no particular topographic pattern. Channels cutting the plateau are short, poorly developed, and debouch into small mud flats. West and southwest, outliers of Wasia (Sakaka) form small plateaus or cap isolated hills.

Sparse measurements indicate that the thickness of the Wasia increases irregularly but persistently from south to north. Some 25 to 30 m thick near Wadi ad Dawasir, the section expands to about 40 m at Wadi as Sahba', 60 m near Khashm Khafs, 80 to 100 m east of Al Majma' ah (lat 25°55' N.), 90 m at Tibah' (lat 27°24' N.), and reaches a maximum thickness of 285 m near Sakakah. Exposures west and southwest of Sakakah are incomplete, and the thickest interval measured at Al Halwat (lat 28°50' N., long 38°42' E.) is somewhat less than 90 m.

LITHOLOGIC CHARACTER

The Wasia (Sakaka) Formation is a relatively thin sandstone and shale unit which is at least in part marine in the central and northern areas and probably nonmarine in the south. In the vicinity of Wasi', a lenticular bed of red sandy dolomite and a local lens

of soft nodular limestone containing marine fossils occur 25 m below the top of the formation. South of Wādī Sahbā' similar lenticular beds of carbonate are known in the same part of the section. Several interbeds of dolomite have also been observed in the sequence at Qibā'.

Wasia rock types south of An Nafūd are characterized by the type succession at Wasī'—a succession measured by R. A. Bramkamp and S. J. Roach in 1955. Their description of the interval is given in section 50 (p. 142).

A substantial thickness of Wasia (Sakaka) crops out in northwestern Arabia. Here again, sandstone, siltstone, and shale are the main rock types present. The 285-m interval exposed in the vicinity of Sakākāh was summarized by D. A. Holm and S. D. Bowers in 1952 as given in section 51 (p. 143).

In Al Hūj plateau, 88 m of Wasia (Sakaka) cap Al Halwāt (lat 28°50' N., long 38°42' E.), and 71 m are at the top of Bārūd (lat 29°03' N., long 38°24' E.). At both places lower beds are conspicuously crossbedded, but the upper part is massive bedded and weathers to heavy ledges; at Al Halwāt, the sandstone is slightly calcareous toward the top, and there is a mud-pellet conglomerate 11 m below the summit.

NATURE OF CONTACT WITH ADJACENT FORMATIONS

At the base of the Wasia is a profound unconformity that cuts into progressively older beds from south to north around the arc of outcrop. From Wādī ad Dāwsir to Ruḥayyat al Hamrā' (lat 24°50' N.) truncation of rocks, in this case the Biyadh, takes place at a rate of up to 1 m per km. Northwestward, the rate of truncation increases to about 3 m per km and the Biyadh is completely overlapped near Wādī al 'Atk. From there, the Wasia progressively transgresses and finally truncates and overlaps the entire Mesozoic section and west of Sakākāh rests on Lower Devonian rocks.

The Wasia Formation is everywhere in disconformable contact with the overlying Aruma. From Wādī as Sahbā' nearly to Sakākāh, the break is clearly marked by a change from sandstone below to reddish-brown, coarsely crystalline dolomite and dolomitic limestone above.

Around the rim of the Sakākāh basin (starting near lat 30°00' N., long 40°30' E.) most of the lower part of the Aruma limestone is replaced by sandstone. As a consequence, the top of the Wasia is somewhat more difficult to pick, but fortunately, a very thin bed of limestone marks the basal Aruma over much of the area. In fact, it is the geometry of this bed that shows the Wasia (Sakaka) to be truncated by pre-Aruma erosion near long 38°30' N.

Aruma happenings in the north are almost perfectly mirrored by events in the south. Just below Wādī as Sahbā', Aruma limestone is replaced from the bottom up by sandstone, thus masking the lower contact. Diligent tracing of beds, including phototracing, has, however, permitted accurate placement of the Wasia-Aruma unconformity south to the termination of Aruma outcrops (at Wādī ad Dawāsir).

PALEONTOLOGY AND AGE

Comments on the ammonite fauna have been supplied by W. M. Furnish (written commun., July 25, 1953). A dolomite bed about 25 m below the top of the Wasia carries the ammonite *Neolobites vibrayeanus* d'Orbigny. A single specimen was collected near Wasī'; several others were found near Qibā'. According to Basse (1937), this species is known from many localities around the Mediterranean and is a fair index for upper Cenomanian.

Fossils collected just north of Wādī al 'Atk on an extensive low bench formed by the upper dolomite bed of the Wasia consisted almost entirely of poorly preserved small gastropods, simple pelecypods, and a solitary coral. None have direct counterparts in any collection from the overlying Aruma. Two fragmentary, poorly preserved ammonites were also collected from this locality. The ammonites show some differences when compared with *Libyoceras* from the overlying Aruma Formation, and they are not close to the *Neolobites* found elsewhere in the Wasia. The worn suture, however, appears to show a relationship to the genus *Knemicerias* s.l., and on this basis the logical deduction would be a Middle Cretaceous age assignment.

Surface-subsurface relationships are not entirely clear (see discussion of Biyadh Sandstone, p. 74) but it seems certain that beds now assigned to the Wasia in central Arabia correspond approximately to the middle part of the coastal Wasia well succession, an interval that roughly involves the Ahmadi and Rumaila Members which are confidently dated on contained microfossils as Cenomanian. It is uncertain whether the overlying Mishrif Member (Turonian) extends as far as the outcrop area, but it is possible that at least part of it does. Consequently, the surface sequence is now dated as Cenomanian and Turonian(?).

ECONOMIC ASPECTS

GROUND WATER

The Wasia aquifer is a thick, widespread hydraulic unit of Middle Cretaceous age that crops out in central Najd and dips gently eastward, maintaining its water-bearing characteristics at least as far as Bahrain. It is composed primarily of permeable, unindurated

sand which throughout most of the Eastern Province is considered a single hydraulic unit. Lithologically and hydraulically, the aquifer becomes more complex toward the Persian Gulf and in the coastal area is separated into two distinct major and possibly several minor units. The Wasia has an established hydraulic gradient which ranges from water-table conditions at and near the outcrop to flowing artesian conditions along the Persian Gulf.

The catchment area consists of: (1) an approximately 25,000-sq km intake belt, a lowland hydrophysiographic province which includes the Wasia and Biyadh outcrop and overlying Tertiary and Quaternary sediments and (2) a nearly 75,000-sq km runoff belt, a highland hydrophysiographic province which is underlain by relatively impermeable pre-Biyadh carbonates. Recharge occurs by two methods—that is, direct percolation in the intake area and subsurface inflow through the channel systems which primarily drain the limestone highlands. The sand- and gravel-filled channels which cross the intake area act as a recharging mechanism during the entire year.

Wasia water ranges in quality from excellent at or near the outcrop where it is freshly meteoric to brine toward the northeast where it represents post-depositionally modified connate water. Oil-field structural features along the coast have a marked effect upon the gentle, east-dipping hydraulic gradient and upon water quality. Restricted permeability on the flanks of structures tends to divert regional flow and restricts flushing by fresher meteoric water, with the result that the older connate water is partially retained. In a converse manner, recharge funneled along the projected axis of the Wādī as Sahbā' trough favorably affects the regional gradient and water quality.

Extraction of Wasia water is confined to three small areas: (1) At and near the outcrop for irrigation and limited domestic uses, (2) at Khurayr for domestic and drilling water supply, and (3) at North Abqaiq for injection of nonpotable water into the oil reservoir.

The aquifer has a large potential for development as a source of supply for domestic use and irrigation, except where it is poor in quality in the northeastern area, along the Persian Gulf coast, and on structure. The most favorable areas for development are those areas where the aquifer will produce good quality water and the intake area, especially in the vicinity of the transintake channels.

PETROLEUM

The Wasia Formation contains commercially productive oil at several levels in the offshore field of Safaniya. Here Wasia rocks apparently record the growth of a great delta, and thin, laterally persistent

sheets of limestone are sandwiched between thick bodies of complexly lenticular sandstone, siltstone, and shale. Individual limestone layers are roughly contemporaneous across the structure and over large parts of northeastern Saudi Arabia. They serve to subdivide and correlate the intervening, often barren, clastic sequences. Although friable sandstone serves as the main reservoir rock, significant quantities of oil have also been discovered in porous limestone beds.

In addition to the Safaniya accumulation, gas occurs in the Wasia at Dammam field and a minor amount of low-gravity oil was detected at Khursaniyah. The Wasia is a highly important producing interval outside of Saudi Arabia as well, particularly in Bahrain, Kuwait, and Iraq.

ARUMA FORMATION—UPPER CRETACEOUS

DEFINITION

The Aruma Formation was named for its occurrence in the Al 'Aramah plateau, a broad upland surface related to the easternmost of the Najd escarpments. Limits of the formation stand essentially as they were originally described by H. L. Burchfiel and J. W. Hoover in 1935.

First formal reference to the Aruma appears in Steineke and Bramkamp (1952b). This was followed in 1958 (Steineke and others) by a detailed description of the type locality. The type sequence was composited from several sections measured along a traverse from Khashim Khanāšir (lat 25°38'12" N., long 46°22'29" E.) northeast to a point on the back slope of Al 'Aramah escarpment (lat 25°39'18" N., long 46°23'30" E.), thence northeast to a promontory (at lat 25°44'35" N., long 46°30'41" E.) in which the top of the formation is exposed.

The base is at the contact of Aruma carbonate rocks with underlying varicolored clastic sediments of the Wasia Formation. The upper limit is taken at the change from yellow-brown dolomitic shale below to gray crystalline *Lockhartia*-bearing dolomite of the Umm er Radhuma Formation above.

OCCURRENCE AND THICKNESS

Rocks of the Aruma Formation crop out from Wādī ad Dawāšir to beyond the Iraq-Saudi Arabia border, a distance of more than 1,600 km. Over this distance the strike of the outcrop belt changes gradually from northeast to north to northwest, describing a great arc wrapped around the central Arabian arch. As the belt approaches Iraq it again swings gently north, probably in response to another positive basement and Paleozoic feature—the Hā'il arch.

Width of the Aruma outcrop band is somewhat erratic, but from a regional point of view it persistently

increases from south to north. About 20 km wide at Wādī ad Dawāsīr, the formation is spread out over nearly 200 km where it passes into Iraq.

In addition to the main belt of outcrop described above, the Aruma can be traced around the northwest margin of the Jawf-Sakākāh basin and then almost continuously along a south-facing escarpment from lat 29°57' N., long 39°44' E. to lat 29°56' N., long 39°18' E. This scarp roughly outlines the northern limit of the Aṭ Tawīl-Aṭ Ṭubayq plateau. Exposures are again picked up in the face of the escarpment between lat 29°41' N., long 39°23' E. and lat 29°32' N., long 39°19' E. Following the scarp around, Aruma beds come in once again and can be mapped almost continuously from lat 29°26' N., long 38°30' E. to where the formation crosses into Jordan near Ṭhāniyat Ṭurayf (lat 29°41' N.). Aruma remnants are also preserved in down-dropped blocks at Umm Nukhaylah and Jabal ar Ri'atayn (lat 30°05' N., long 39°41' E.).

It should be pointed out that the two patches of Aruma shown in the Al Harrah lava field (U.S. Geological Survey-Arabian-American Oil Co., 1963)—lat 30° 46' N., long 39°13' E. and lat 30°40' N., long 39°20' E.—are in error. These areas are, in fact, gravel-covered, and there is no evidence that Aruma rocks were deposited here.

The Aruma outcrop belt is breached at only a few places by surficial cover. In the south, exposures are masked by gravel outwash from Wādī al Maqran and Wādī al Jadwal (lat 22°00' N.). In the central area, Aruma beds are down dropped into the Wādī as Sahbā' structural trough and covered by channel fill. Structural complications also appear to be responsible for interruptions at Wādī al 'Atk and along Al Buṭayn (roughly from Wādī al 'Atk to Umm al Jamā'im, lat 26°52' N., long 45°18' E.). In the latter, a wide, northwest-trending sheet of locally derived gravel is banked on the east against a sharp monocline involving Aruma rocks. Sand of An Nafūd severs the outcrop belt along lat 28°50' N. where it encroaches east nearly far enough to merge with sand of Ad Dahna'.

The western edge of Aruma limestone is characteristically a steep cliff that can be recognized around Sakākāh and south from An Nafūd to Wādī Jabaliyah (lat 22°25' N.). Generally the scarp is coincident with the western limit of the formation, but south of Wādī as Sahbā' it becomes progressively lower and moves eastward diagonally across the outcrop band as the limestone is replaced from the bottom up by less resistant sandstone.

The back slope of the Al'Aramah escarpment forms the great plateaus of Al 'Aramah, At Taysiyah, and Al Widyān north from Wādī as Sahbā' and of Huraysān

to the south. As a whole, the Al 'Aramah plateau is well dissected by channels cut perpendicular to the face of the main scarp. This is particularly true in the areas of At Taysiyah and Al Widyān where the surface is broken by an intricate drainage complex.

A series of small faults break through the Aruma around the structurally active Jawf-Sakākāh basin. The faults routinely strike about N. 20° W. and appear to be either vertical or dip at very high angles. Most show low-order vertical displacement (probably less than 15 m); horizontal movement is not apparent as drag folds, shear fractures, and offset features are lacking. The faults are apparently related to adjustments in older beds.

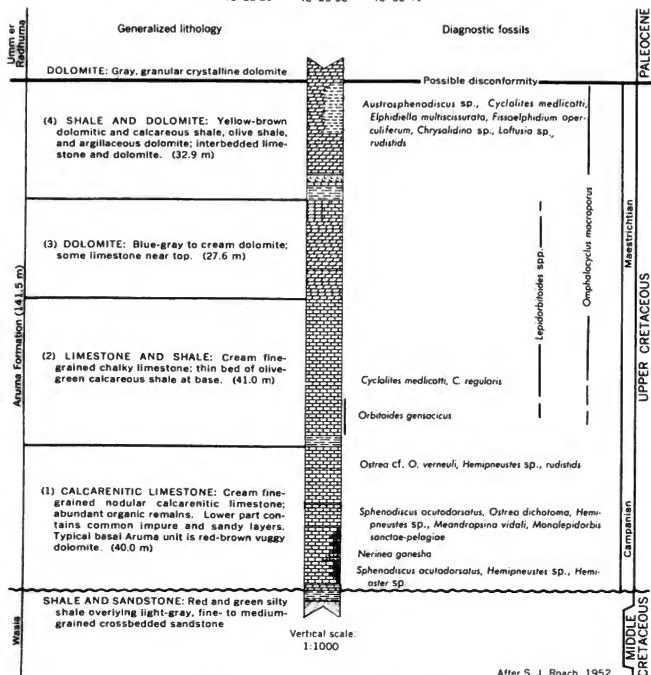
The Aruma Formation is calculated to be about 60 m thick near where the unit passes under the Rub' al Khali sand. This same approximate thickness is maintained northward nearly to lat 22°30' N. and then the formation progressively thickens to about 130 m at Wādī as Sahbā' and 140 m at the type locality (lat 25°40' N.). The same approximate thickness is apparently maintained to the north, as an interval measured west of Sakākāh indicates about 145 m of Aruma in this area. Some thinning is apparent around the margin of the Jawf-Sakākāh basin, and intervals measured along the northern edge of the Aṭ Tawīl-Aṭ Ṭubayq range from about 5 to 35 m.

LITHOLOGIC CHARACTER

In the extensive area from Wādī as Sahbā' to Sakākāh, the Aruma Formation is mainly shallow-water limestone, in part replaced by massive dolomite. Subordinate shale and impure dolomite are present, particularly in the upper 25 to 35 m. Locally, rudistids and other heavy-shelled molluscs are abundant enough to form biostromes.

The rock types and lithologic sequence of the Aruma Formation throughout the Wādī as Sahbā' -Sakākāh belt are characteristically displayed at the type locality. This sequence (fig. 10) was measured just south of Wādī al 'Atk by Roach in 1952. He recognized two units that served to group most of the shale and impure carbonate into a single member—the Lina—overlying a somewhat cleaner carbonate sequence—the Atj member. This subdivision, never formally adopted, has some merit, as Redmond has demonstrated a disconformable contact between the two members, a contact that has widespread subsurface expression with significant angular discordance. Unfortunately, the lateral continuity of the two units has never been systematically demonstrated beyond the limits of Al 'Aramah plateau. A detailed description of the type sequence is given in section 52 (p. 143).

Location:
 25°38'12" to 25°39'18" to 25°44'35"
 46°22'29" to 46°23'30" to 46°30'41"



After S. J. Roach, 1952

FIGURE 10.—Aruma Formation type section.

Lateral changes in the Aruma Formation south of Wādī as Sahbā' consist mainly of a gradual replacement of limestone by sandstone from the bottom up. First hints of the replacement can be seen about 40 km south of the wādī; progressive transition from carbonate to sandstone continues so that in the vicinity of Wādī Jabaliyah (lat 22°25' N.) the Aruma is sandstone only. This facies persists to the southern limit of outcrop.

In the northern part of the Aruma outcrop, relatively marked changes occur with the appearance of a major lens of sandstone in the lower part of the section. At Khashm Zallūm (lat 30°18' N., long 40°21' E.) 61 m of sandstone overlies an 11-m-thick basal Aruma limestone unit. Some investigators have suggested that the top of this limestone corresponds to the top of the Atj member at the type locality. This relationship has yet to be proved; if it is correct, then lower beds of an expanded Lina member are involved in the limestone-to-sandstone transition. The sandstone—informally termed the Zallūm sandstone—is locally poorly indurated, fine to medium grained, and made up of subrounded grains. Striking colors of white, gray, brown, and purple prevail, particularly on weathered surfaces. Near the base, concentrations of cobbles and pebbles of chert, quartz, and quartzite are locally common. In places, the sandstone is now an orthoquartzite which weathers into hard, dark-gray boulders.

From Khashm Zallūm the sandstone can be traced southwest in the face of Jāl al Amghar to Khashm al Makhrūq (lat 30°03' N., long 40°40' E.) and then east for about 15 to 20 km where it thins slightly and undergoes a rapid facies change to marly dolomite, dolomite, and limestone—rocks that are typical of the Aruma further south. Northeast of Khashm Zallūm, the sandstone crops out in the upper reaches of Wādī 'Ar 'ar directly under Aruma limestone and can be traced in the deeply incised canyons as far as Al Mu' tadil (lat 30°31' N., long 40°27' E.); it cannot be identified with certainty north of this point.

The Zallūm sandstone is not exposed in the Aruma limestone escarpment northwest of Sakākah but has been identified as the caprock on Jabal Qiyāl al Kabir (lat 30°06' N., long 40°05' E.) on the northwestern flank of the basin. Zallūm sandstone again comes to the surface (at lat 29°57' N., long 39°40' E.) in an escarpment that closely parallels the unconformable contact between Paleozoic and Eocene or Cretaceous rocks. Sporadic outcrops of Zallūm, the only Aruma unit appearing west of long 39°40' E., have been mapped in the face of this scarp as far as the Saudi Arabian-Jordan border. With the exception of the Zallūm lens, Aruma rock types and fossils in the northern Al Widyān region are very similar to those occurring further south.

NATURE OF CONTACT WITH ADJACENT FORMATIONS

Over most of the outcrop the Aruma rests disconformably on the Wasia. Between Wādī as Sahbā' and the vicinity of Sakākah, the contact is easily placed at the break from sandstone and shale below to limestone above. South of Wādī as Sahbā', the Aruma is mainly in clastic facies, and the contact is less clear. Even here, however, the contact is marked by a change from silty sandstone and siltstone below to sandstone above.

In the vicinity of Sakākah, the Wasia (Sakaka)-Aruma contact emerges from under the blanket sand of An Nafūd and can be traced along the eastern and northwestern edge of the basin. The break between the two units is definitely unconformable, and over this distance Aruma limestone rests on successively older parts of the Wasia (Sakaka); near Al Murayr (lat 30°03' N., long 39°55' E.) the Wasia (Sakaka) is overlapped, and Aruma rests directly on Lower Devonian (Jauf) beds. Not far to the southwest the limestone pinches out. At the next outcrop (at lat 29°57' N., long 39°40' E.) the Zallūm sandstone facies is the only vestige of the Aruma left, and at this point it is lapped onto the Tawil Sandstone Member of the Tabuk Formation. Sporadic outcrops of Zallūm (to the west and south along the Al Jayb scarp and west again across the northern edge of the At Tawil-At Tubayq plateau) rest on beds of the Tawil Member and, in one area west of Umm Nukhaylah, on beds of the Jauf Formation.

Along its eastern margin, the Aruma is everywhere overlain by the Umm er Radhuma Formation. The contact has for many years been considered conformable and gradational, but there is some subsurface paleontologic evidence that at least locally a disconformity separates the two. Some paleontologists (R. Page, unpub. data, 1959) have suggested that the contact over all Saudi Arabia represents a disconformity—or more accurately, a paraconformity (contact is a simple bedding plane); for on outcrop and in deep wells, the top Aruma unit is a thin bed of blue-gray to black dolomitic shale bearing *Fissolophidium operculiferum* Smout, *Loftusia* spp., and *Omphalocyclus macroporus* Lamarck. Immediately above is limestone or dolomite with definite lower Paleocene microfossils. The mechanics of formation of a paraconformity of such magnitude and regularity is difficult to imagine.

North of Sakākah, the Aruma Formation is overlain by a cherty, nummulitic limestone of Paleocene or Eocene age that was apparently not directly related to the Umm er Radhuma basin of deposition. Little work has been done in this area, and the exact nature of the contact is unknown.

PALEONTOLOGY AND AGE

There is some possibility that the lowermost beds of the Aruma outcrop could be as old as Santonian, as they contain *Meandropina vidali* Schlumberger, a form originally described from the Santonian of Spain. However, the uppermost occurrence of this form in Saudi Arabia overlaps the range of *Monolepidorhis sanctae-pelagiae* Astre, a Campanian form likewise originally described from Spain.

The middle part of the Aruma Formation presents a problem in that it contains beds which fall below the level of the lowermost definitely Maestrichtian Foraminifera and above the level of the uppermost definitely Campanian Foraminifera.

Immediately overlying this anomalous interval are beds which carry abundant occurrences of *Orbitoides genascicus* (Leymerie) and *Omphalocyclus macroporus* (Lamarck), both good Maestrichtian markers with a very wide distribution in Europe.

Omphalocyclus macroporus is known to occur within a meter of the top of the formation, thus placing the uppermost beds of the Aruma within the Maestrichtian. Other forms occurring within the upper part of the Aruma are *Elphidiella multiciccurata* Smout, *Fissolophium operculiferum*, *Chrysalidina* sp., and *Lepidorbitoides* sp. The latter appear to be limited to the middle and lower parts of the range of *Omphalocyclus macroporus*.

It is interesting to note that the outcrop Aruma is completely lacking in pelagic Foraminifera, though these are abundantly represented in the deep wells of the coastal area. On the basis of its Foraminifera the Aruma on outcrop is apparently Campanian and Maestrichtian, a conclusion consistent with ammonite and other fossil evidence.

A comprehensive fossil list for the Aruma Formation includes: *Cyclolites medlicotti* Noetling, *Cyclolites regularis* Lamarck, *Cyclolites* spp., *Coral* spp., *Goniopygus* sp., *Hemiasper* sp., *Hemipneustes* spp., *Holactypus* sp., *Parapygus* aff. *P. inflatus* Cotteau and Gauthier, *Pygostoma* aff. *P. morgani* Cotteau and Gauthier, cidaroid spines, *Anomalina* sp., *Anomalinella* cf. *A. rostrata* (Brady), *Atazophragium* sp., "*Borelis*" sp., *Cibicides* sp., *Cyclammina* sp., *Fallotia*? sp., *Globigerina* sp., *Globotruncana* spp., *Haplophragmoides* sp., *Lepidorbitoides* sp., *Loftusia* sp., *Meandropina* sp., *Omphalocyclus* sp., *Orbitoides* sp., *Planispirina* sp., *Præsores*? sp., *Pyrgo* sp., *Quinqueloculina* spp., *Rotalia* sp., cf. *Valvulinaria* sp., miliolids, *Actinophyma*? sp., *Agethesia* sp., *Alaria* sp., *Amavropsis* sp., *Ancilla* sp., *Anomia* sp., *Aporrhais* sp., *Arca* sp., *Arrhoges* sp., *Anaphis* sp., *Barbatia* sp., *Bellardia* sp., *Bournonia* sp., *Bullaria*? sp., *Calliostoma* cf. *C. omanicus* Lees, *Cal-*

lostoma sp., *Campanile* sp., cf. *Campanile* sp., *Cardita* cf. *C. beaumonti* d'Archiac, *Cardium* sp., *Cardium*? sp., *Cerastoderma*? sp., *Chione*? sp., *Chlamys* sp., *Chlamys*? dujardini (Roemer) Noetling, *Corbis* sp., *Corbula* sp., *Cranis*? sp., *Crassatella* sp., *Crassatella*? sp., *Criocerat*? sp., *Cymatium* sp., *Cymatium*? sp., *Eocypraea* sp., *Euspira* sp., *Faunus* sp., *Ficus* sp., *Glycimeris* sp., *Harpagodes*? sp., *Hippochrenes* sp., *Indoceras baluchistanensis* Noetling, *Inoceramus* sp., *Keilostoma* sp., *Lambis*? sp., *Lima* sp., *Mitra*? sp., *Mytilus*? sp., *Monodonta*? sp., *Morgania*? sp., *Nautilus* (Heminautilus) sp., *Nautilus* spp., *Neithea quadricostata* (Sowerby), *Nemocardium*? sp., *Nerinea ganesha* Noetling, *Nerita* cf. *N. pontica* (d'Archiac) Noetling, *Orthechinus* aff. *O. cretaceus* Cotteau and Gauthier, *Orthopsis* sp., *Ostrea dichotoma* Boyle, *Ostrea* cf. *O. verneuli* Leymerie, *Ovula* sp., *Pecten* sp., *Perissolaz*? sp., *Pholadomya* cf. *P. tigris* Noetling, *Pholadomya* sp., "*Pleurotomaria*" sp., *Plicatula* cf. *P. hirsuta* Conrad, *Potomides* sp., *Protocardium*? sp., *Pugnella* aff. *P. orientalis* Lees, *Pyrazus* spp., *Pyrgulifera*? sp., *Pyrrina orientalis* Cotteau and Gauthier, *Pyrrula*? sp., *Sassia* sp., *Scaphella* spp., *Spondylus* spp., *Sphenodiscus* cf. *S. acutodorsatus* Noetling, *Sphenodiscus* spp., *Sycostoma*? sp., *Tegula* sp., *Tibia* sp., *Tresinus* sp., *Trochus*? sp., *Tudoceras*? sp., *Turbo* sp., *Turbo*? sp., *Turritella* cf. *T. guttensis* Noetling, *Turritella* sp., *Tylostoma* sp., *Venericardia* sp., *Umbonium* sp., *Volvulina* sp., *Xenophora*? sp., ostracodes, and crab claws.

ECONOMIC ASPECTS

GROUND WATER

The Aruma aquifer has an established hydraulic gradient ranging from water-table conditions on or near the outcrop to flowing artesian conditions in the eastern and southeastern Rub' al Khāl. Conditions in northeastern Arabia are less well known. Hydraulic factors are complicated by stratigraphic changes, and water-bearing zones probably constitute only a minor part of the total section.

Aruma water has been tested for quality and quantity in only a few widely scattered areas. Such sparse information suggests that the eastern edge of potable water will pass south of Hafar al Bātin, near Al Lihābah, along the western flank of the Ghawar oil field, and then south through the Rub' al Khāl along the 50th meridian.

The Aruma aquifer has been developed as a permanent water supply source only in a few restricted areas. The pipeline stations at Rafāh and Badanah are supplied by wells completed in the Aruma; artesian rises are small, and yield of the wells is comparatively low.

TERTIARY SYSTEM

UMM ER RADHUMA FORMATION—PALEOCENE AND LOWER EOCENE

DEFINITION

The Umm er Radhuma Formation was named by S. B. Henry and C. W. Brown in 1935 for the Umm Radmah wells (lat 28°41' N., long 44°41' E.) that draw water from the upper part of the unit. In 1936, Max Steineke and J. W. Hoover also studied the formation in this area but, because of difficulties in working out a full sequence, designated a reference section in Wādī al Bāṭin. Umm er Radhuma was first cited in publication by Steineke and Bramkamp (1952(b)); a later paper (Steineke and others, 1958) included reference section details.

With exception of the uppermost beds, the entire formation can be seen in the steep walls of Wādī al Bāṭin. Here, the reference section was pieced together from many short intervals measured in a continuous 70-km traverse from the top of the Līnah escarpment (lat 27°38'03" N., long 44°53'24" E.) northeast along Al Bāṭin to lat 27°59'00" N., long 45°27'48" E.

The base of the Umm er Radhuma is at the contact of *Lockhartia*-bearing dolomite and limestone with underlying dolomitic shale of the Aruma Formation. The top is not exposed at the reference section because of overlapping Miocene and Pliocene rocks, but it is present a short distance down dip in structure holes and water wells where Umm er Radhuma dolomite containing *Lockhartia huntii* Ovey var. *pustulosa* Smut is overlain by soft chalky Rus limestone.

OCCURRENCE AND THICKNESS

Rocks of the Umm er Radhuma have been mapped in a fairly wide belt extending from just south of Wādī Jabalyah (lat 22°25' N.) to the Iraq-Saudi Arabian border, a distance of about 1,200 km. Width of the Umm er Radhuma is highly variable, in some places because of superficial sand and gravel cover, in others because of overlapping Miocene and Pliocene beds. Prior to such cover, however, the outcrop probably was quite regular, measuring 60 km across at the south and about 120 km near Iraq, most of the expansion apparently taking place between Khurays (lat 25°05' N.) and Ma' qalā' (lat 26°32' N.).

From Wādī al Bāṭin south, the Umm er Radhuma is longitudinally disrupted by the great curved Ad Dahnā' sand belt, a cover that effectively prevents study of any complete section throughout this distance. At the southern limit of the Umm er Radhuma, upper beds are masked. Northward the Ad Dahnā' sand belt shifts, covers the middle part of the formation nearly to Al Bāṭin, and then, as strike of the Umm er

Radhuma swings north, cuts sharply across section and overlaps the Aruma.

Umm er Radhuma exposures usually form a gently undulating but rough surface spotted with low isolated hills and weak discontinuous benches. Karst features are a prominent part of the upland surface, particularly northwest of Al Bāṭin. This area also supports a well-developed system of through-cutting channels that follow regional dip.

In the area southwest of the Trans-Arabian Pipeline, between Ash Shu'bah (lat 28°54' N., long 44°42' E.) and Rafḥā' (lat 29°39' N., long 43°28' E.), the Umm er Radhuma surface is marked by numerous elevated river channels which begin at the Līnah escarpment and trend northeast to the Umm er Radhuma scarp where the majority of them are covered. Together with their tributaries they form a dendritic pattern which bears little relationship to the present drainage system and none to present structure. Their present elevation, from 2 to 18 m above the local base level, was probably caused by subsequent deflation of the softer intervening rocks. Miller (1937) discussed these bas-relief drainage lines.

The elevated channels and tributaries, each with varying thicknesses of duricrust, are separated by low, enclosed silt basins which collect present runoff. Upper surfaces of the tributaries slope toward the main channels at gradients ranging from 2° to 4°, whereas beds of channel deposits making up the elevated tributaries have a more gradual dip (from 00°30' to 1°30') in the same direction. Channel deposits are most commonly marl and limestone derived from the Umm er Radhuma, but, in the northwest, rocks of the upper Aruma are included as well.

Much of the area northwest of Al Bāṭin is characterized by a very poorly developed internal drainage system related to numerous small sinks and major sharp scarps, such as Jāl Nawāzīr-Mahshim U'aywīj, 35 km west of Rafḥā', and Jāl al Baṭn, 60 km north of Rafḥā'. Within Saudi Arabia, the highest of these monoclinical escarpments—Jāl al Baṭn—extends between Al Lifiyah (lat 30°25' N., long 43°04' E.) and Birkat al 'Aqabah (lat 30°05' N., long 43°37' E.), roughly a distance of 65 km. Although its trend is generally northwest, the face of the flexure is quite sinuous and dips variously to the west, southwest, and south. Regional dip on the upland surface, about 00°10' NE., is maintained to the crest of the jāl where it abruptly shifts to a maximum of 12° in the opposite direction along the front-face dip slope. At the foot of the slope the rate of dip gradually slackens and merges once again with the regional. The greatest relief measured along Jāl al Baṭn from the rim of the base of the escarpment was 85 m. A similar flexure—Mahshim U'aywīj-Jāl Nawāzīr—occurs about

35 km west of Rafhā'. Its strike is north-northwest with the dip slope facing southwest. In many respects it is similar to Jāl al Baṭn, although its maximum relief is only 35 m. Slumping involves Umm er Radhuma as well as a few isolated patches of Miocene and Pliocene. The steepest dips on the face are 10°.

Tested by drilling, these two monoclines have proven to be superficial, primarily related to solution-collapse caused by removal of anhydrite. Shallow holes bracketing the flexure show a thick interbed of Umm er Radhuma anhydrite immediately below the surface on the structurally high side of the monocline; the anhydrite is missing on the low side.

Within the Umm er Radhuma outcrop area many Miocene and Pliocene slump features occur around or near the periphery of the larger Miocene and Pliocene bodies. Domes at Al Liffyah, Lawqah (lat 29°49' N., long 42°45' E.), and Kharmā' Karīm (lat 29°00' N., long 44°47' E.) are examples. These and other related domal structures are characterized by concentric rings of limestone ridges about 5 m in relief and generally occurring about 100 m apart. Some such as Kharmā' Karīm are more than 5 km in diameter at the outside ledge. Dip on the ledges is about 4° to 8° radially away from the center of the dome, but there is no appreciable difference in the elevation of the tops of the rings. It is presumed on the basis of stratigraphic position and lithologic similarity that the limestone ridges represent repetition of beds in section rather than continuous depositional sequence. This repetition is attributed in part to solution of underlying evaporites and in part to "draping" of the Miocene and Pliocene sediments over "hills" on the overlapped Umm er Radhuma surface.

Surface mapping and structure drilling indicate that these anomalous surface features involving Miocene and Pliocene, Umm er Radhuma, and, in some instances, Aruma strata are superficial solution-collapse structures. Their mode of formation in Miocene and Pliocene rocks is still incompletely understood but in older beds now seems clear.

In addition to the main outcrop belt, rocks at least partly equivalent to the Umm er Radhuma (and overlying Rus and Dammam) are exposed over much of the area north of lat 29°30' N. and west of the 40th meridian. Nearly 160 km of Aruma separates the two areas of Paleocene and Eocene sedimentation. The undivided Paleocene and Eocene rocks on the west—informally termed the Hibr formation—are presumably a Mediterranean facies deposited in a seaway not directly connected with the Persian Gulf basin.

Maximum known thickness of the Umm er Radhuma on outcrop is at the reference section where 243 m was measured. To the south, the Ad Dahmā' sand

cover and loss of beds at the top through pre-Miocene erosion prevents accurate measurement. However, partial measurements supplemented by calculated intervals show about 105 m near Wādī al 'Atk and 110 m at Wādī as Sahbā'. North of the reference section, two sections have been pieced together from numerous very short increments measured along highly circuitous traverses. The first, extending generally northeast to Niṣāb (lat 29°11' N., long 44°43' E.), indicated about 210 m; the second (approximately along lat 30°00' N.) showed 234 m but did not reach the top of the formation. Another traverse in the extreme northwestern corner of Saudi Arabia indicated only 25 m of Umm er Radhuma below the pre-Miocene unconformity.

So far as the Hibr formation is concerned, E. L. Berg and L. D. Owens in 1946 measured 150 m of beds between Ḥazm al Jalāmīd (lat 31°18' N., long 39°54' E.) and Tall al Hibr (lat 31°51' N., long 38°08' E.). Their measurement appears short in view of the fact that a water well drilled at Turayf pump station (lat 31°41' N., long 38°39' E.) penetrated nearly 485 m of Hibr beds.

In the northern part of Wādī as Sirḥān (near lat 31°30' N., long 37°05' E.), in 1952 D. A. Holm and others measured 110 m of section above the Hibr that is now regarded as upper Eocene and possibly is even in part Oligocene. Lateral extent of the upper Eocene has never been determined, and it has therefore been necessary simply to consider it along with Hibr strata as Paleocene and Eocene undivided.

LITHOLOGIC CHARACTER

The Umm er Radhuma everywhere consists of a repetitious series of light-colored foraminiferal aphanitic and calcarenitic limestone, dolomitic limestone, and dolomite. Local silicification of thin, bench-capping limestones is common, and chert occurs sporadically throughout the section. Although certain distinctive beds are found at various levels, it is difficult to find any group of beds that can be set apart as a unit. The best that can be said is that calcarenitic and siliceous beds are more common in the upper part of the formation and partially dolomitized aphanitic limestone in the lower. Regionally, there seems to be progressive replacement of limestone by dolomite from south to north although there are significant exceptions to even this pattern.

The middle part of the Umm er Radhuma is covered by eolian sand for some distance north and south of Wādī as Sahbā'. Here, approximately the uppermost 50 m of the formation is exposed east of the sand blanket, and in addition approximately 30 m of basal beds crop out to the west. The missing interval covered

by sand is unknown but is considered to be relatively small and is estimated to represent about 30 m of section. Throughout this area, the Umm er Radhuma is entirely limestone except for a thin laterally persistent zone of dolomite and partially dolomitized limestone at the top. In the north the dolomite crops out as a wide bench below the Rus escarpment. The bench can again be picked up to the south of Wādī as Sahbā', but capping Rus beds are missing because of Miocene and Pliocene overlap. Below the zone of dolomite is a uniform succession of gray-green to tan, finely granular, somewhat leached and chalky limestone. Fossiliferous beds occur at many levels, but the fossils have usually been leached out, their only trace being small pits on the weathered surface.

Rocks of the Umm er Radhuma north of Al Bātin are accurately represented by the reference sequence measured and described in that channel. Max Steineke and J. W. Hoover in 1936 were the first to work the Al Bātin section and define it as a reference locality. Because rates of dip of the channel bottom and of the flanking bedding are so nearly alike, only 3 to 4 m of new beds are exposed per kilometer. It is somewhat difficult to trace such low-dipping beds in a monotonous sequence and accurately tie together the many small increments making up a full section. As a result, W. H. Reiss and R. D. MacDougall in 1953 retraced the original traverse and with plane-table survey remeasured the entire outcrop band (pl. 10). Their description of the reference section is given in section 53 (p. 143).

Like the Umm er Radhuma-Rus-Dammam (Paleocene to middle Eocene) sequence to which it most closely equates, the Hibr is also almost exclusively limestone. The unit is composed of light-colored, thin-bedded, chalky and cherty limestone and marl. Partial dolomitization is common. Nummulite and other fossil zones occur at several levels, but no consistent marker beds have been observed. Much chert is interbedded with chalky limestone in the form of lenses, platy masses, flat ovoid nodules, and spheroidal concretions. Parts of the upper Hibr, for example between Turayf and Tall al Hibr, have been altered to tripoli, a fine powdery form of silica. On weathering, the Hibr forms a rather flat, featureless plain. Included chert often remains as residual chips after removal of surrounding softer limestone by weathering and deflation.

NATURE OF CONTACT WITH ADJACENT FORMATIONS

The Umm er Radhuma everywhere overlies the Aruma with apparent conformity. Precise characteristics of the contact have already been pointed out in the discussion of the upper Aruma limit (p. 82).

The contact of the Hibr rocks with underlying units is less clear. On the east, it overlies the Aruma For-

mation with the boundary generally trending north-south along long 39°50' E. The base of the Hibr has been defined as the contact with the underlying Cretaceous, which is a somewhat tenuous limit. It has been necessary to set an arbitrary base at the break between beds containing abundant dark chert and, in some areas, *Nummulites* and beds of nonsiliceous carbonates of the Aruma. The problem of the Cretaceous-Eocene contact does not exist, of course, where Cretaceous beds are missing for example, 20 km north-west of Al Jawf. Here Paleocene beds lap over onto Lower Devonian strata. Immediately west, however, the Aruma (Zallum sandstone facies) appears between, and in discordant relationship with, Hibr and Paleozoic rocks. A comparable situation prevails around the southern margin of the Hibr as far as the Jordan border; that is, Paleocene and Eocene rocks unconformably overlie Zallum where it is present but otherwise rest directly on Lower Devonian.

Contact between the Umm er Radhuma and the overlying Rus Formation is visible only from Wādī as Sahbā' north to lat 25°44' N., a distance of 180 km. Over this distance, dolomite and dolomitized limestone of the Umm er Radhuma is conformably overlain by typical soft, chalky limestone of the Rus Formation. Outside of this area, the Umm er Radhuma is unconformably terminated at the top by erratic outcrops of sandy marl and sandy limestone (Miocene and Pliocene) or surficial deposits.

Western exposures of Paleocene and Eocene undivided (including Hibr facies) are discordantly overlain by sandy carbonates (Miocene and Pliocene) or by flows of Tertiary and Quaternary basalt.

PALEONTOLOGY AND AGE

The Umm er Radhuma Formation falls into three principal subdivisions on faunal grounds. The upper division is early Eocene in age; it carries such species as *Sakesaria colteri* Davies, *Lockhartia tipperi* (Davies), and *Lockhartia huntii* Ovey var. *pustulosa* Smout. It is equivalent to the lower Eocene of Qatar described by Smout (1954) and the Laki beds of India.

The two lower subdivisions are Paleocene in age, the break between them probably corresponding to the contact between Smout's Qatar Paleocene zones 4 and 5 (Smout, 1954). These lower subdivisions of the Umm er Radhuma correspond at least in part to the Ranikot of India, but exactly what part of the Ranikot is represented in the Saudi Arabian beds is not known. However, the general parallelism between the beds of the lowermost Umm er Radhuma and the uppermost (Maestrichtian) beds of the Aruma would not suggest any prolonged time gap at the contact.

Originally considered Eocene and Oligocene, the post-Arma sediments northwest of Sakakah are now fairly accurately dated as Paleocene to late Eocene. Nautiloids of Paleocene affinities were collected at the base of the section (according to W. M. Furnish, referring to *Comomia* sp. cf. *C. kugleri* Miller). Strong evidence for a Paleocene age was also given by recovery of *Anomalina dorri* Cole var. *aragoneis* Nuttall, *Bulimina semicostata* Nuttall, *Globorotalia relacensis* (Cushman), *Loxostoma applinae* (Plummer), and *Siphogenerina eleganta* Plummer from a Turayf water well. Higher beds in this Turayf well carry *Bulimina jacksonensis* Cushman and *Hantkenina mexicana* Cushman, forms indicative of either Middle or Upper Eocene age. Correlative beds on the outcrop, however, also carry abundant occurrences of *Nummulites gizehensis* (Forakel), thus suggesting that most of the higher beds at Turayf belong within the Middle Eocene. The presence of Upper Eocene is not proved but is postulated on the occurrence of post-Hibr beds still carrying *B. jacksonensis* and on the occurrence of beds above the range of *B. jacksonensis* but within the biozone of *Gumbelina*.

A comprehensive faunal list of the Umm er Radhuma and Paleocene-Eocene undivided (including Hibr facies) is given below.

The Umm er Radhuma Formation contains *Opisthomeris somaliensis*?, indeterminate echinoids, *Anadara* sp., *Arca*? sp., *Brachiodontes*? sp., *Bullaria* sp., *Cardita*? sp., *Cerithium* (s.l.) sp., *Chama*? sp., *Corbula* sp., *Cymatium* spp., *Diplodonta*? sp., *Euspira* cf. *E. roci*, *Homalopoma*? sp., *Macoma*? sp., *Nautilus* sp., *Nemocardium*? sp., *Oliva*? sp., *Pentalium*? sp., *Siliqua* cf. sp., *Strepsidura* sp., *Turritella* sp., indeterminate lucinid, naticoid, cerithiid, and strombid gastropods. Foraminifera are poorly preserved and not abundant on outcrop. See plate 10 for representative subsurface forms.

The Paleocene and Eocene undivided (including Hibr facies) contains *Amphiope*? sp., *Echinocymus libycus*? Fourtan, *Cardita* cf. *C. asperula*, *Cassia nilotica*?, *Dalmanys*, *Conus*, *Comomia* cf. *C. kugleri*, *Lucina* sp., *Mesolia hofana*, *M. locardi*, *Ostrea plicata*? Solander, *Turritella* sp., *Venericardia* sp., shark teeth, *Amphisorus*?, *Assilina*?, *Bulimina*?, *Clavulina* sp., *Globigerina*, *Nummulites curvispira* d'Archiac and Haime, *N.* spp., *Operculina* cf. *O. discoidea* Schwager, *Quinqueloculina* sp., *Textularia*?, *Uvigerina*, *Valulina* spp., *Valvulinaria*.

ECONOMIC ASPECTS

GROUND WATER

The Umm er Radhuma aquifer is a single thick hydraulic unit of regional extent. It has an established gradient ranging from water-table conditions on

or near the outcrop to flowing artesian conditions along the Persian Gulf and in some topographically low areas of the Rub' al Khali. The catchment area for this aquifer is the belt of Aruma and Umm er Radhuma outcrop plus the area mantled by eolian sand of Ad Dahna'.

Water from the Umm er Radhuma ranges in quality from excellent at or near the outcrop to poor generally northwest of the Trans-Arabian Pipeline. Some areas within the general region of potability, such as Nariya, Abqaiq, and Ras Tanura, produce poor-quality water because of the presence of dissolved hydrogen sulfide gas. In the Rub' al Khali, water with less than 4,800 ppm of total dissolved solids occurs as far east as the 51st meridian. East of this line and generally north of the 21st parallel, total solids vary from 5,000 to 95,000 ppm.

Local structural features in the coastal area have some effect on water quality and also upon the east-dipping hydraulic gradient. A decrease in permeability on the flanks of the features tends to divert regional flow and to restrict flushing by fresher meteoric water. This effect is not as marked, however, as it is in the Wasia.

The Umm er Radhuma aquifer has been developed by Aramco as the water supply for many of the company communities and outlying installations. Potential of the aquifer is such that it could also handily support major domestic and agricultural projects.

RUS FORMATION—LOWER EOCENE

DEFINITION

The Rus Formation is named for Umm ar Ru'us (lat 26°19' N., long 50°08' E.), a small hill where the type section was measured. R. A. Bramkamp first applied the name in 1946 as a direct replacement for the term "Chalky Zone" which had been informally used for lower Eocene beds above the Umm er Radhuma and below the Dammam Formation. The limits have not been changed.

A table of Saudi Arabian rock units appearing in a paper by Thralls and Hasson (1956) constitutes first formal publication of the term Rus Formation. Detailed information on the type sequence was published by Steineke, Bramkamp, and Sander (1958). Additional stratigraphic and paleontologic data was included in Sander's (1962) discussion.

The type section of the "Chalk Zone," now the Rus Formation, was originally established by S. B. Henry and J. W. Hoover in 1934 on the southeastern flank of Dammam Dome in and below Umm ar Ru'us (lat 26°19'04" N., long 50°07'51" E.).

The base is at the contact between brown dolomite containing *Lockhartia huntii* Ovey var. *pustulosa* Smout

below and light-colored, chalky, partially dolomitized limestone above. Common leached molds of small indeterminate molluscs is a marked characteristic of the basal Rus unit. The upper few meters of the Rus is not exposed at the type locality but can be picked up clearly in the adjacent rimrock around Dammam Dome. Here the break is at the change from light-colored, chalky calcarenite below to yellow-brown shale of the basal member of the Dammam Formation above.

OCCURRENCE AND THICKNESS

Definite exposures of Rus rocks are limited to two small areas—the first, a narrow band extending some 180 km northward from Wādī as Sahbā', and the second, a nearly circular patch about 10 km in diameter cropping out in the breached core of Dammam Dome.

The Rus north of Wādī as Sahbā' is rather featureless, without a traceable bed or other reliable guide to stratigraphic position. For this reason the full thickness can only be estimated as 25 to 30 m. Thickness at the type locality is 56 m.

A number of isolated patches in the far southeastern Rub' al Khālī, north of Dhufar, have been mapped as Rus and Dammam undivided, but the exact makeup of these outliers is uncertain. Paleocene and Eocene rocks (Hibr) occurring northwest of Sakākah, certainly in part equivalent to the Rus, have been described in connection with the Umm er Radhuma.

LITHOLOGIC CHARACTER

Rock types in the two areas of Rus outcrop are for all practical purposes identical. Basically, the unit is light-colored, soft, chalky limestone and marl. R. A. Bramkamp's remeasurement of the Umm ar Ru'ūs sequence in 1946 (fig. 11) resulted in the description given in section 54 (p. 145), which is typical for other exposures as well.

Subsurface equivalents of the middle Rus (unit 2, section 54 and fig. 11) are highly variable both in lithology and thickness. Most commonly the sequence is (1) white, compact, finely crystalline anhydrite with interbedded green shale or (2) gray marl with coarsely crystalline calcite and interbedded shale and limestone. Variations in thickness are largely caused by variations in the amount of anhydrite present. As a general rule, the middle Rus is thicker on the flanks of structures than it is on the crests. Complexly settled rocks, such as those seen around Dammam Dome, suggest some of the differences in interval are caused by solution of anhydrite. In other places, the differences seem to be related to original depositional thinning over structural highs.

NATURE OF CONTACT WITH ADJACENT FORMATIONS

The Rus in the vicinity of Wādī as Sahbā' represents an unbroken transition from the Umm er Radhuma below to the Dammam above. In spite of the uniformity of section, contacts are reasonable clear cut. Brown Umm er Radhuma dolomite is overlain by off-white, chalky, porous limestone with abundant indeterminate molds and casts, which in turn gives way at the top to tan, calcareous, and gypsiferous shale and interbedded marl of the basal Dammam.

Comparable breaks mark the top and bottom of the Rus at Dammam Dome.

PALaeONTOLOGY AND AGE

Diagnostic fossils are not known to occur in the Rus Formation although it is underlain and overlain by rocks of proven early Eocene age. In terms of standard European stages the Rus is presumed to fall entirely within the Ypresian.

ECONOMIC ASPECTS

As a dominantly evaporite sequence, the Rus has few porous beds. Limestones at the base and top of the interval are porous and probably water bearing, but these have not been selectively tested. Some shows of low-gravity oil have been found in offshore wells.

DAMMAM FORMATION—LOWER AND MIDDLE EOCENE DEFINITION

The Dammam Formation was named for Dammam Dome where the entire sequence crops out. R. A. Bramkamp in 1941 measured and designated the type locality along the old Dhahran-Al 'Alāh road from the point where this road intersects the rimrock (lat 26°19'16" N., long 50°04'50" E.) northwest to the Eocene-Miocene contact.

The base is at the contact of calcarenite or limestone of the Rus Formation with the overlying brown shale and light-gray marl of the basal Dammam. The top is at the unconformable contact of pure carbonate of any part of the Dammam Formation with the overlying sandy limestone of the Hadruk Formation.

Where present in full thickness, the Dammam is almost everywhere divisible into five members, two of which possess distinctive and laterally persistent basal marl units. Listed in descending order, these members and their subdivisions are as follows:

Alat Member:

Alat limestone

Alat marl

Khobar Member:

Khobar dolomite

Khobar marl

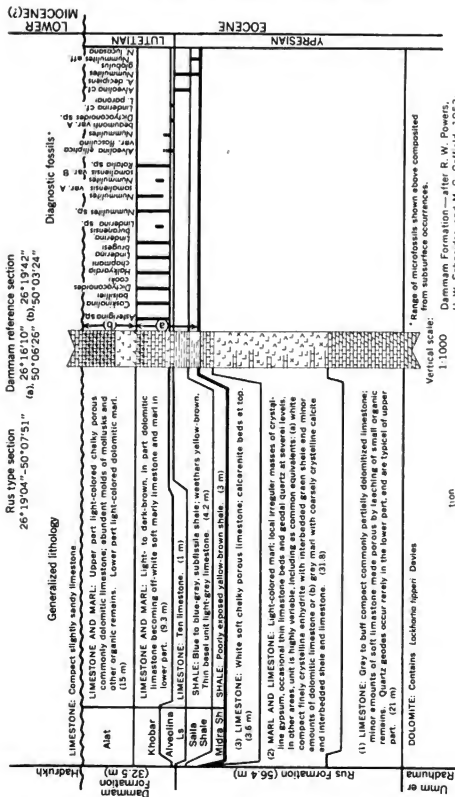


FIGURE 11.—Dammam and Rus Formations type and reference sections.

Alveolina Limestone Member
Saila Shale Member
Midra Shale Member

The Alat Member takes its name from Al Alat well 1 (lat 26°27'49" N., long 49°50'11" E.), where the upper part of the member is exposed nearby and the lower part is represented by the drilled interval from 0 to 67 m. Alat beds are best displayed in a low hill at lat 26°19'42" N., long 50°03'24" E., and this section is herewith designated as the type locality.

Here, as elsewhere, the upper part of the member is limestone (9.0 m), the lower part, marl (6.0 m). The lower marl was for many years informally referred to as the "Orange marl," but the name is now obsolete. The top of the Alat is at the unconformable contact of light-colored, chalky dolomitic limestone below with sandy limestone of the Hadruk Formation above. The base is taken at the break from dolomitic marl above to dolomite or dolomitic limestone (with abundant *Nummulites*) of the Khobar Member below.

Pre-Alat members of the Dammam Formation are exposed at several places along the rimrock of Dammam Dome, but one of the best sections is that southwest of Umm ar Ru'ūs at lat 26°16'10" N., long 50°06'26" E. This sequence is herewith designated as the type locality for the Khobar, Alveolina, Saila, and Midra Members.

The Khobar Member is named for the town of Al Khobar (lat 26°17' N., long 50°13' E.) on the eastern edge of the Dammam Dome rimrock. Characteristically, the upper part of the unit is limestone, and the lower part, marl; at the type section, thicknesses are 7.8 and 1.5 m respectively. The name of the upper limestone was originally proposed as "Khobar dolomite (and limestone) member," but usage has reduced this to "Khobar dolomite" in spite of the fact that limestone and marl are far more typical of this part of the section. There are, of course, some places where dolomite predominates, but these places are scarce.

The top of the Khobar is placed at the contact of *Nummulites*-bearing dolomitic limestone or dolomite below with marl of the Alat Member above. The base falls at the change from *Nummulitic* marl above to *Alveolina*-bearing limestone below.

The Alveolina Limestone Member, only 1.0 m thick at the type section, characteristically contains common specimens of *Alveolina elliptica* (Sowerby) var. *fusculina* Silvestri. The top of the member is picked on a lithologic break from marl to limestone and is confirmed by fauna. The base is placed at the level where tan *Alveolina*-bearing limestone gives way downward to blue and gray-blue shale or marl of the Saila Shale Member.

At the type locality the Saila Shale Member consists of 3.6 m of brownish-yellow subsiliceous clay shale underlain by 0.6 m of gray limestone. The top of the member is placed at the contact of Alveolina Limestone Member above with blue-tinted shale below. A thin limestone which usually occurs at the base of the shale is grouped with it, and the lower limit of the Saila is considered to fall at the contact between this limestone and underlying yellow-brown shale of the Midra Member.

The basal member of the Dammam Formation—the Midra Shale Member (originally "Shark Tooth shale," informal and obsolete)—is 3.0 m thick at the type section. The top is picked solely on lithology. It is placed at the uppermost occurrence of yellow-brown earthy clay shale below limestone of the Saila Member. The base is at the contact between yellow-brown shale or gray marl above and soft chalky limestone or calcarenite of the Rus Formation below.

OCCURRENCE AND THICKNESS

Outcrops of the Dammam Formation are limited to a number of small but widely scattered patches north of Wādī as Sahbā', near the coast, and in the south-eastern Rub' al Khālī.

Dammam beds crop out in a narrow irregular band from Wādī as Sahbā' to lat 25°41' N., a distance of nearly 180 km. The band, usually less than 5 km wide, includes a somewhat low discontinuous escarpment on the west. A probable maximum of 15 m of basal Dammam is exposed above the Umm ar Radhuma and under the Miocene and Pliocene overlap.

A full Dammam sequence is exposed in the conspicuous oval-shaped escarpment rimming Dammam Dome. Average inside diameter of the ring of Dammam rocks is about 10 km; average outside diameter is 18 km. A maximum formation thickness of 32.5 m has been measured between the Rus center and the surrounding cover. Four small outliers of Dammam have been mapped generally west of the dome and north of Abqaiq and another near Harāq (lat 24°08' N., long 49°04' E.) at the southern end of Ghawar oil field.

A relatively large exposure of Dammam, about 20 sq km, occurs at the base of the Qatar Peninsula. For the most part the rocks are Dammam, but occasional windows of Rus can be seen in low hollows. Thickness of the section here varies from 10 to 51 m, encompassing the Midra, Saila, Alveolina and Khobar Members.

Numerous isolated exposures of Dammam and of Rus and Dammam undivided along the eastern and southeastern margin of the Rub' al Khālī show that Eocene rocks floor a substantial area beneath eolian sand cover. Nothing is known of the precise thickness or members represented.

LITHOLOGIC CHARACTER

Rocks of the Dammam Formation are characteristically light-colored limestone, marl, and shale. There is no significant variation from the rock types at Dammam Dome, even though the Dammam Formation and its individual members thicken drastically in the subsurface and extend over most of northeastern Arabia and large parts of the Rub' al Khālī.

Best exposures are those of the Dammam Formation reference section which also serves as the type locality for the separate members. The section was pieced together by R. W. Powers and others in 1953 from two measurements (fig. 11): the lower covering the Midra-Saila-Alveolina-Khobar interval, the upper including Alat strata. Reference section particulars have been given in connection with member definition (p. 88). A detailed description of the rock sequence is given in section 55 (p. 145).

NATURE OF CONTACT WITH ADJACENT FORMATIONS

The base of the Dammam Formation is exposed only at Dammam Dome and in the vicinity of Wādī as Sahbā'. In both areas, shale of the Midra Member rests conformably on chalky limestone of the Rus Formation. At the top, various members of the Dammam are in discordant contact with Miocene and Pliocene or with younger sediments.

PALAEONTOLOGY AND AGE

From the uppermost beds of the Alat Member, which carry a very large *Dictyoncus* sp., to the base of the Alveolina Limestone Member with *Alveolina elliptica* (Sowerby) var. *floeculina* Silvestri, the Dammam Formation is clearly middle Eocene (Lutetian) in age. Below this level the presence of a "*Nummulites globulus* Leymerie" of the type figured by Smout (1954) from the lower Eocene of Qatar strongly indicates that the remainder of the formation is lower Eocene (Ypresian).

Microfossils are usually poorly preserved on outcrop, and the diagnostic forms shown in figure 11 have been projected into the reference section from the subsurface sequence. Correlations are clear cut, and there is no doubt about surface-subsurface relationships.

ECONOMIC ASPECTS

GROUND WATER

Two carbonate members of the Dammam Formation—the Khobar and Alat—are aquifers of regional importance. As in pre-Dammam aquifers, both hydraulic and salinity gradients are evident. Artesian conditions occur near the western outcrop band, and flowing artesian conditions obtain in the coastal area and eastern Rub' al Khālī. Likewise, the breakover from potable to nonpotable water follows roughly the

same pattern as that established by the Umm er Radhuma. Recharge to both aquifers is apparently provided by downward percolation through Miocene and Pliocene sands overlying the truncated outcrop.

Khobar water is used extensively in communities and agricultural areas of the Eastern Province. Al Qatif oasis, north of Dhahran, and the towns of Al Qatif and Al Khubar as well as adjacent communities constitute the most concentrated areas of withdrawal. A few wells have penetrated the Khobar aquifer in and near the oasis of Al Hasā.

Major withdrawals from the Alat aquifer are also limited to the Eastern Province. The member is the sole source of potable water for the towns of Ras Tanura and the pump station at An Nu' ayriyah. Locale of heaviest development, however, is in Al Qatif oasis. Erratic artesian conditions prevail in this area, and it is necessary in many places to drill through the Alat and complete in the Khobar to obtain flowing water.

HADRUKH, DAM, HOFUF, AND KHARJ FORMATIONS—
MIOCENE AND PIOCENE

DEFINITION

The coastal area of Saudi Arabia has been essentially a broad structural terrace, only intermittently submerged, throughout Tertiary time. As a result, few marine sediments were deposited during that period, and these only erratically as seas oscillated to and fro across the terrace with each invasion reaching varying distances inland. The most western margin of marine sedimentation seems to be generally less than 100 km from the present Persian Gulf shoreline.

Where marine rocks occur, the Miocene and Pliocene succession can be subdivided into three formations which from the bottom up are Hadruk, Dam, and Hofuf. Toward the interior, marine marker beds grade to continental sediments, and coastal subdivisions can no longer be recognized. Where this happens, the above formations are treated as a single unit—Tertiary sandstone, marl, and limestone. Beyond the western limit of the continental beds, distinctive patches of lake deposits, generally plastered on the Sulayy outcrop belt, have been named the Kharj Formation. Of presumed Miocene and Pliocene age, they are certainly at least in part equivalent to Tertiary marine-continental rocks to the east.

The names Hadruk, Dam, and Hofuf were first used in 1935 by Max Steineke and T. W. Koch as phases and later formations of the coastal Miocene and Pliocene succession. In a formal sense, the names first appeared in a paper by Thralls and Hasson (1956); type section details are given in a paper by Steineke, Bramkamp, and Sander (1958).

The Hadruk Formation was named for Jabal al Haydarük (lat 27°04'36" N., long 49°11'24" E.) where the upper part of the type sequence is exposed. In 1935 Steineke and Koch measured and defined the type locality by taking the upper 51.5 m in the south face of Jabal al Haydarük and the lower 32.5 m from a shallow hand-dug well about 1500 m to the southeast.

Generally the basal bed of the Hadruk is a few meters of cream, slightly sandy limestone. This rests unconformably on nonsandy, marine Eocene limestone. The top is at the contact of calcareous sandstone below with *Echinocyanus*-bearing limestone and marl of the basal Dam above.

The Dam Formation is named for Jabal al Lidām (lat 26°21'42" N., long 49°27'42" E.) where the lower part of the type unit crops out. Formation limits were set in 1935 by Steineke and Koch who measured the lower beds in the east face of Jabal al Lidām and the upper part of the 89.8-m interval at Al Umayghir (lat 26°17'15" N., long 49°30'24" E.).

At the type locality, the base of the Dam is placed at the change from sandstone of the Hadruk below to fossiliferous marl with *Echinocyanus* above. The top is at the contact between marl and limestone with marine fossils of the Dam and overlying clay, sandstone, and gravel of the basal Hofuf.

The Hofuf Formation takes its name from the town of Al Hufuf (lat 25°22' N., long 49°35' E.) about 15 km south-southwest of the type locality. In establishing the type sequence in 1935, Steineke and Koch measured the lower 78 m at the southern end of Barqā' Rukbān (lat 25°30'48" N., long 49°31'18" E.) and an additional 17 m in exposures to the west and northwest, giving a total of 95 m.

The base of the Hofuf is at the contact of generally quartz-pebble-bearing beds above with calcareous rocks of the Dam below. The top is at the upper limits of the exposures of the Al Hufuf area, commonly an old duricrust-covered surface.

The Kharij Formation takes its name from the area of Al Kharij in the upper reaches of Wādī as Sahbā'. Although R. A. Bramkamp and T. C. Barger studied Kharij beds as early as 1938, the unit was never formally named until 1956 (Bramkamp and others). No type locality has been designated; however, the unit is typically displayed in a small hill about 3 km north-northeast of Khashim Khuraysah (lat 23°34' N., long 47°07' E.). Here, 28.1 m of Kharij rocks was measured and described.

OCCURRENCE AND THICKNESS

Rocks of Miocene and Pliocene age cover a large area that extends from Wādī ad Dawṣir to the northern boundary of Saudi Arabia. The western edge com-

monly falls within the Paleocene and Eocene outcrop band; the eastern edge is usually marked by sand of the Rub' al Khālī-Al Jāfūrah belt and the Persian Gulf shoreline. To be sure, several exposures are outside this general area, but most of these are small and little known. Three, however, are large and worth noting: the first forms a thin strip along the eastern edge of Al Jāfūrah from Jibāl al 'Uqayr (lat 25°34' N.) to the vicinity of Al Jawb al Ḥadārī (near lat 23°20' N.); the second is an elongated, discontinuous band flooring Wādī as Sirbān in the northwest (just east of the Saudi Arabian-Jordan boundary) and flanking the At Tawīl plateau in the southeast; and the third occurs as isolated patches on the surface of Al Hūj. In addition, Miocene and Pliocene rocks are exposed in small windows in the Rub' al Khālī sand around 'Urūq ibn Ḥamūdāh (lat 18°50' N., long 51°50' E.) and in a wide, east-west belt generally between lat 21°00' N. and 22°30' N. and extending from the 49th to the 53d meridian. The latter deposits, while at least in part equivalent to the Miocene and Pliocene of other areas, probably contain some Quaternary elements as well and, for this reason, have been depicted on Miscellaneous Geologic Investigations Maps as Tertiary and Quaternary marl.

As stated before, the presence of marine strata near the coast permits subdivision of Miocene and Pliocene rocks of this area into three formations which are, from bottom to top, the Hadruk, Dam, and Hofuf.

Rocks of the Hadruk Formation cover a lowland belt roughly 100 km wide along the coast from the Saudi Arabia-Kuwait Neutral Zone almost to Abqaiq. Some outliers occur as far inland as 200 km, for example, near Jabal al Khafaq (lat 26°55' N., long 47°15' E.) and in windows in the band of eolian sand blanketing the Abqaiq-Al Qatīf area.

Thickness of the Hadruk, as would be expected, is highly variable, ranging from 20 m in the Abqaiq-Al Qatīf area to 90 m near Jabal al Lidām (lat 26°22' N., long 49°38' E.). Still greater thicknesses of up to 120 m were recorded around Abū Ḥadriyah (lat 27°20' N., long 48°57' E.) and to the northwest.

Residual patches of Dam rocks show that the middle Miocene sea transgressed roughly 120 km inland from the modern coastline and covered an extensive area from south of Qatar to the eastern edge and around the northern end of Ghawar and then on to Jibāl an Nu'ayriyah (lat 27°31' N., long 48°23' E.). This is a distance of about 450 km measured parallel to the coast. Around the margins, marine rocks of the Dam give way rapidly to continental deposits, complete gradation often taking place in as short a distance as 10 km.

Thickness of the Dam Formation varies considerably. About 90 m is exposed at the type locality, but else-

where as little as 30 m and as much as 100 m have been found to represent a full section.

The largest single exposure of the Hofuf Formation is superimposed on Ghawar field and almost perfectly mirrors the outline of that giant oil-filled anticline. The northern part of the structure is reflected in Hofuf beds at the surface by a prominent, dissected plateau capped by a resistant limestone layer. The preservation of the plateau seems to result from carbonate enrichment of its surface over the anticline, this enrichment giving it greater resistance to erosion there than in the synclinal areas. In southern Ghawar, the resistant cap is not as thick, and only patches of it remain. Here, Hofuf beds stand somewhat higher than the surrounding area but are much less prominent topographically than in the north.

Outside the immediate Ghawar area important exposures of the Hofuf (1) extend in a very thin band from Jibāl al Kharāniq (lat 26°13' N., long 48°55' E.) northwest for about 70 km, (2) follow the Al 'Uqayr escarpment southeast from Jibāl al 'Uqayr (lat 25°34' N., long 50°04' E.) to the 24th parallel, (3) occur as small outliers north and northeast of Al Huffuf, and (4) cap Jabal al Kharīmā (lat 25°05' N., long 49°38' E.) and several isolated hills to the south.

At the type locality the Hofuf Formation is 95 m thick; measurements in other areas show definite variation from this figure. The thinnest sequence is about 30 m, and the maximum, somewhat more than 100 m.

With the disappearance of the marine deposits of the Dam Formation toward the interior, it is impossible to subdivide the all-continental Miocene and Pliocene succession. Distribution of the continental series corresponds roughly to the extensive Aş Şumman plateau bordering the Paleocene and Eocene outcrop north of lat 22°20' N. Southward, Miocene and Pliocene beds carry the Aş Şumman surface across the Umm er Radhuma and overlap onto Upper Cretaceous.

In the north, bore holes indicate that continental beds form a wedge increasing from 0 m on the west to about 100 m where they merge with the marine facies. Thickening in the south is more drastic, reaching as much as 300 m before passing under the sands of the Rub' al Khālī.

Irregular patches of the Kharj Formation, roughly contemporaneous with the Miocene and Pliocene units described above, dot the landscape in front of the Hit escarpment. For the most part, Kharj rocks are confined to the Sulaiy outcrop belt between Wādī al 'Atk and lat 23°15' N., a distance of more than 300 km.

Thicknesses of Kharj deposits measured at two localities are (1) 28 m exposed in a small hill a few kilometers north of Khashm Khuraysah and (2) about 9 m in the

vicinity of Ashqar Marāghah (lat 24°20' N., long 47°06' E.).

LITHOLOGIC CHARACTER

Miocene and Pliocene rocks are characteristically varicolored sandstone, sandy marl, and sandy limestone. Lenses of shale and conglomerate are common, gypsum and chert are present locally.

Rocks of the Hadruk Formation are nonmarine except in a small area outlined by Al Qattif, Al 'Alāh, Jabal Qurayn (lat 26°39' N., long 49°37' E.) and Al Jubayl al Barri (lat 26°54' N., long 49°38' E.). Over this region, a few thin layers near the top of the formation contain poorly preserved marine molluscs. Hadruk rocks are mainly green, grayish green, and gray, but red, brown, white, and pink colors are also common. Marly sandstone, sandy marl, sandy clay, and sandy limestone make up most of the unit; chert is common at some levels, and minor amounts of gypsum are also present.

The formation is typically exposed at Jabal al Haydarūk, the type locality (fig. 12) established by Max Steineke and T. W. Koch in 1935. Their description is given in section 56 (p. 145).

The Dam Formation is pink, white, and gray marl and red, green, and olive clay with minor interbeds of sandstone, chalky limestone, and coquina. Marine fossils are abundant throughout the unit, but the best marker zones are near the base. Of these, the "Button bed" composed of large numbers of small echinoids, *Echinoecyamus* sp., and the closely associated "*Archais*" sp. bed are undoubtedly the most widespread. They have been recognized throughout the area of Dam outcrop.

The Dam type locality selected by Steineke and Koch in 1935 serves well to characterize sediments of that formation (fig. 13). A measurement and description at Jabal al Lidām is given in section 57 (p. 146).

In the coastal east-facing escarpments, the marine Dam Formation is overlain by continental deposits of conglomerate, sandstone, sandy limestone, sandy marl, and sandy shale assigned to the Hofuf Formation. The upper beds consist of sandy fresh-water limestone which caps not only the coastal exposures but the greater part of the interior Aş Şumman plateau region as well.

The type section measured in 1935 by Steineke and Koch north of Al Huffuf is as representative a sequence as can be expected in such a heterogeneous and lenticular body of rocks (fig. 14). Their description is given in section 58 (p. 146).

The most interesting feature of the Hofuf Formation is the great areal extent over which gravel deposits of this unit and its interior equivalent are found. Apparently at the end of Dam time there was a general

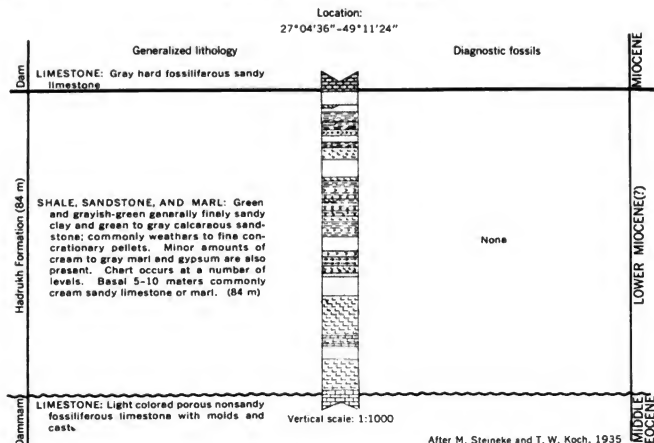


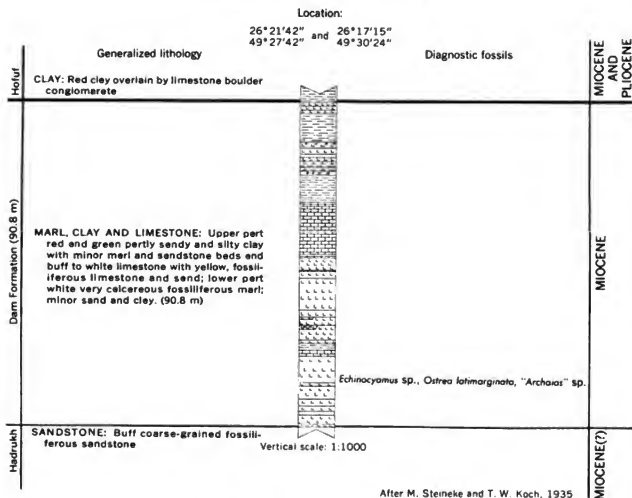
FIGURE 12.—Hadrukh Formation type section.

tilting of the Arabian foreland and a rapid erosion of the interior region which furnished the gravel incorporated in the Hofuf. Usually the gravels consist of quartz, various types of igneous rocks, and metamorphic rocks. In some places such as the type locality, the pebbles and boulders are recognizable limestone quite definitely derived from Jabal Tuwayq (Upper Jurassic) units. As a result, it is possible that individual silicate grains might have been brought in from lenticular conglomerates in the Cretaceous, Triassic, or Cambrian to Devonian. It seems more likely though that the bulk of them came more or less directly from the basement complex.

Gravel lenses are found locally in the Hadrukh and Dam Formations, but the size of the pebbles is always small, generally less than 25 mm in diameter. On the other hand, gravels of the Hofuf are as much as 125 mm in diameter. In places a thin veneer of loose lag gravel is spread over vast areas of the Miocene outcrop surface. In the vicinity of Al Hufuf and in the area south of Qatar, isolated mesa hills of the Hofuf Formation conspicuously protrude above the surrounding gravel-

covered plains. These hills commonly contain conglomeratic beds, and it is believed that the widespread, uniform distribution of the gravels results from desert erosion of the Hofuf, the heavier, resistant constituents remaining as residual or lag gravels.

In the Şumman, Wadi as Sirbān, At Tawil, and Al Hāj areas, Miocene and Pliocene deposits are wholly continental and generally consist of a heterogeneous series of red to reddish-brown, gray and rarely off-white, calcareous sandstone, sandy marl, poorly sorted sandy shale, and impure, sandy, fresh-water limestone. Only the sequence at Al Hāj shows any significant variation from this general assemblage. Here the oldest of the Miocene and Pliocene rocks is a conglomerate which is locally as thick as 30 m. Although the conglomerate lies upon the Jauf Formation, it is extraneous to the Jauf and is a discrete rock unit which seems to represent eroded remnants of bajadas which formed during one of the pluvial periods—possibly in the later Tertiary. If these conglomeratic deposits are the remains of a series of confluent alluvial fans, then much of the material must have been eroded from hills which are



After M. Steineke and T. W. Koch, 1935

FIGURE 13.—Dam Formation type section.

now standing amid the deposits as isolated peaks or cones. Dip angles suggest that the detritus was originally deposited around these cones but that a later period of erosion cut the land to its present aspect, removed much of the conglomerate blanket, and exhumed the Al Huj surface.

These conglomerates have not been found elsewhere and apparently are unique to Al Huj. The size of the grains varies locally. Close to the high cones the conglomerates are literally boulder beds, made up of large blocks of sandstone and limestone eroded from the Jauf and the Wasia (Sakaka) Formations. Further away, the clastics are smaller and deposited at lower dip angles. Certainly these deposits can be classed as conglomerates.

The only other partially stratified rocks considered to be of Miocene and Pliocene age are those of the Kharj Formation. In and southward from the area where big channels from Jabal Tuwayq join to form Wadi as

Sahba', Kharj rocks are normally lacustrine limestone with associated bedded gypsum and gravel. Discontinuous exposures of this same general suite of rocks have been located as far south as lat $23^{\circ}15'$ N., east down Wadi as Sahba' to just beyond Jabal at Tayah (lat $24^{\circ}13'$ N., long $47^{\circ}40'$ E.), and alongside the Saudi Government Railroad from lat $24^{\circ}17'$ N. to lat $24^{\circ}30'$ N. North of lat $24^{\circ}30'$ N., the apparent equivalent of the Kharj is poorly exposed gravel composed chiefly of limestone pebbles and cobbles locally cemented by dark, slightly ferruginous caliche.

Lacustrine beds are best developed in the low country just southwest of the Hit escarpment roughly between Dahl Hit and Jabal Mahawiz (lat $24^{\circ}16'$ N., long $47^{\circ}15'$ E.). Here there is normally a resistant fresh-water limestone about 1 m thick resting on several meters of soft beds, mainly gypsum and gypsiferous sand. Poorly preserved fresh-water fossils have been found at several localities.

Location:
25° 30' 48" - 49° 31' 18"

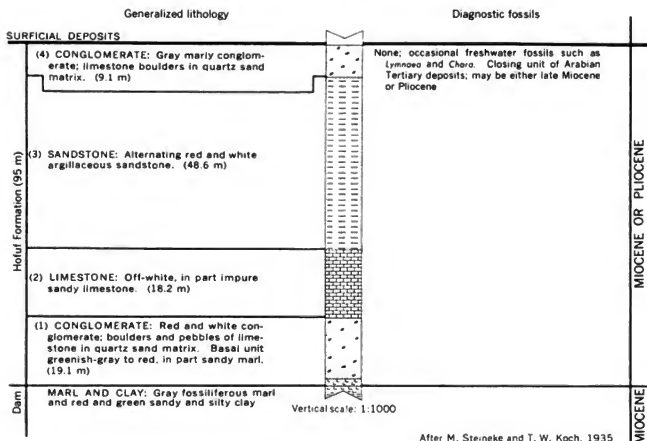


FIGURE 14.—Hofuf Formation type section.

Kharj rocks in fresh-water facies were also studied just north of Khashm Khuraysah (lat 23°34' N., long 47°07' E.) where 28.1 m was measured and described from top to bottom as follows: 3.4 m tan and dark-gray, fresh-water limestone containing botryoidal structure suggestive of algal origin; 1.8 m limestone conglomerate with a coarse and angular component derived from the nearby outcrop of Arab, Sulaiy, Buwaib, and Yamama Formations; and 22.9 m poorly sorted, gravel, conglomerate, and sand, including weathered limestone pebbles and discontinuously bedded conglomerate with calcareous cement.

NATURE OF CONTACT WITH ADJACENT FORMATIONS

Surface and subsurface data show that Miocene and Pliocene units are everywhere in discordant contact with underlying units. Paleocene and Eocene strata are most commonly involved, but in some areas such as the northwestern Rub' al Khālī and near Jordan, Creta-

ceous and even Paleozoic beds are affected. The contact in each locality, however, is relatively simple to pick, as the varicolored lenticular sandy carbonates and sandstones of the Miocene and Pliocene usually contrast sharply with the pure carbonates and bedded clastics of older units.

At the top, Miocene and Pliocene rocks are unconformably overlain, usually by various surficial deposits, but in the far northwest by basalt flows.

PALEONTOLOGY AND AGE

The age of the Hadruk Formation is not specifically established. However, because of its apparent continuity with the overlying Dam Formation, the Hadruk is considered to be early Miocene. Rare non-marine fossils including *Chara* are present, and near the coast a few thin layers near the top of the formation contain poorly preserved marine molluscs and echinoid debris. A complete list of fossils recovered from

Hadruk surface beds includes: *Chara*, *Anomalocardia*? sp., *Cardita* cf., *Cerithium* (*Bellardia*?) sp., *Chlamys* cf. *C. senatoria* (Gmelin), *Clementia papyracea* (Gray)?, *Diplodonta* cf. *D. incerta* d'Archiac and Haime, cf. *Natica*, *Ostrea latimarginata* Verdenburg, *Ostrea* spp., *Turritella gradata*, *Turritella* sp. indeterminate venerid pelecypods, *Echinocyamus*?, crab claws, sharks teeth, cidaroid spines, and fossil wood.

So far as the Dam Formation is concerned, the presence of *Ostrea latimarginata* Vredenburg, *Echinocyamus* sp., and "Archaias" sp. indicates approximate correlation with the Lower Fars Formation of Iraq. On this basis, the Dam is presumed to be about middle Miocene. A complete list of fossils recovered from the Dam Formation includes: *Balanus*, *Agassizia* cf. *A. scrobiculata* Valenciennes, *Agassizia* sp., *Brius latitudinensis* Clegg, *Echinodiscus desori* Duncan and Sladen, *Echinocyamus* sp., *Lorenia elongata* Gray, *Mora adamthi* Clegg, *Schizaster*, *Schizaster*?, *Tenonopleurus persica* Clegg, *Tenonopleurus* sp., cidaroid radiales, *Archaias angulatus* (Fichtel and Moll), *Archaias* sp., *Elphidium*, *Operculina* sp., *Peneroplis* spp., *Quinqueloculina* sp., *Triloculina* sp., miliolids, *Anomia* sp., *Arca* sp., *Bullaria* sp., *Bittium*? sp., *Bursa*? sp., *Calyptraea*? sp., *Cardium*? sp., *Chlamys senatoria*, *Clavacula* sp., *Clementia papyracea* (Gray), *Conus* sp., *Coralliophila*, *Corbicula*? sp., *Diplodonta* cf. *D. incerta* d'Archiac and Haime, *Epitonium*, cf. *Hemifusus*, *Mitra*? sp., *Ostrea angulata* J. de C. Sowerby, *Ostrea latimarginata* Vredenburg, *Ostrea virleti* Deshayes, *Ostrea* cf. *O. virleti*, *Ostrea* spp., *Paphia*? sp., *Placenta* sp., *Strombus*? sp., *Thais*? sp., *Turritella* cf. *T. gradata*, *Turritella* spp., *Volva*? sp., indeterminate corals, fossil wood, vertebrate fragments, crab claws, and ostracodes.

The Hofuf Formation is chiefly unfossiliferous although occasional nondiagnostic fresh-water fossils including *Lymnaea* and *Chara* occur. Since the Hofuf represents the closing unit of the Arabian Tertiary deposits, it may be either late Miocene or Pliocene. A comprehensive fossil list includes *Chara* sp., *Lymnaea* sp., *Planorbis* sp., *Thiara* sp., ostracodes, and indeterminate gastropods.

As Kharj deposits are obviously post-Eocene and pre-Quaternary, they are most certainly Tertiary. No direct evidence bearing on their age has been found except that, if the channel gravels in the various localities are about the same age, they may be roughly contemporaneous with the great gravel flood of the basal Hofuf Formation in the area to the east. Specimens of *Corbicula* sp. and *Melania* sp. are the only fossils so far discovered.

ECONOMIC ASPECTS

GROUND WATER

The water-bearing properties of the Miocene and Pliocene rocks, as might be expected, are erratic. Apparently the sequence carries water regionally, but productive capacity, storage factors, and quality vary sharply both laterally and vertically. Locally, artesian flowing conditions are found, as in a few wells in the Rub' al Khali and in the oases of Al Hasa and Al Qatif, but pumps are required in most areas.

One of the most extensive developments of the Miocene and Pliocene aquifer is around Al Hufuf (Al Hasa) with its many large 'ayns or springs. Great quantities of water are also withdrawn in the Al Qatif oasis where many large springs have developed along the western and northwestern edge of the cultivated area. There is reason to suspect that some of these springs are in hydraulic communication with the Alat (Eocene) aquifer below. Other scattered areas in the Eastern Province are also supplied with Neogene water.

TERTIARY AND QUATERNARY SYSTEMS

GRAVEL

Small, widely scattered, isolated patches of late Tertiary gravel occur: (1) in Wadi Nayyāl (lat 28°30' N., long 39°03' E.), (2) 50 km east of 'Unayzah (lat 26°06' N., long 43°59' E.), (3) 30 km north of Ad Dawādīmī (lat 24°30' N., long 44°23' E.), (4) in and near Wādī as Sahbā' between the Mughrah trough (long 47°30' E.) and long 48°35' E., (5) in Ad Dahnā' 40 km south of Wādī as Sahbā', and (6) at lat 23° N., long 47° E. where a relatively large patch is associated with deposits of the Kharj Formation.

The gravel is dominantly well-rounded white quartz pebbles as large as 10 centimeters in diameter, usually in a poorly sorted, earthy, sandy matrix. Subordinate limestone pebbles are usually present. Thus, lithologically, the gravel resembles rather closely some of the Hofuf gravels farther to the east.

The gravels, ordinarily in trains and in patches on upland surfaces, have not been studied to any extent except in the vicinity of Wādī as Sahbā'. Here they increase in prominence from west to east and no doubt represent an old major drainage channel. It is likely that the Wādī as Sahbā' structural trough was the path by which the old river crossed the present area of the Al 'Aramah escarpment. West of the escarpment channel gravels occur only in one small area, along the axis of the Mughrah trough (generally along lat 24°18' N. and between long 47°30' E. and 47°37' E.). Although they have not been traced continuously and the pattern is obscured by younger fill, two small patches of gravel are present near the western edge of Ad

Dahnā', one 10 km and the other 25 km north of Wādī as Sabhā'. These are well-defined eastward-trending gravel ridges leading east from Ad Dahnā' to the gravel plains around southern Ghawr. These probable links strongly suggest that the channel gravels are remnants of a group of late Tertiary rivers which brought down the great gravel flood incorporated in the lower part of the Hofuf Formation.

The relationship of the channel gravels to fresh-water deposits of the Kharj Formation is unknown even though they are in contact at one locality—that is, near lat 23°16' N. It is tempting to suggest that the channel gravels may be the result of streams that discharged overflow from lakes in which the fresh-water sediments were being deposited, but this suggestion is pure speculation.

TERRACE SAND AND GRAVEL

Terrace deposits of presumed Pliocene age are known only at the northwestern edge of Harrah Hutaym (at lat 26°35' N., long 39°40' E.). Here the rocks are fine-grained gray sandstone and marl with a basal conglomerate. Fresh-water ostracodes are present in the upper part.

A similar deposit of light-gray marl with gastropods and fresh-water ostracodes has recently been discovered near lat 27°26' N., long 38°29' E. (not shown on Miscellaneous Geologic Investigations Maps). The fauna is modern in aspect and can scarcely be older than late Tertiary; it is questionably assigned to the Pliocene. Relationship between this and the Harrah Hutaym patch is still obscure.

MARL AND SANDSTONE

Small outliers of sandy marl, marly sandstone, and sandy limestone occurring in an east-west belt across the central part of the Rub' al Khālī have already been mentioned in connection with similar Tertiary sediments which are certainly in part, if not wholly, equivalent (p. 91).

BASALT

Al Harrah, the only volcanic complex within the sedimentary area of Saudi Arabia, extends from near Ath Thāyāt (lat 30°32' N., long 39°20' E.) northwestward for almost 250 km where it crosses into Jordan. Over this distance, width of the lava field ranges from 80 to 100 km. Younger basalt components of Al Harrah are tentatively assigned to the Quaternary; older elements, informally known as the Garaiyat lavas, are considered to be Miocene and Pliocene.

The younger lavas are chiefly olivine basalt locally with thin aplite dikes. At places they are scoriaceous and vesicular and include bedded pyroclastics, plugs, and cones. Petrographic analysis of a sample from Qitab ash Shāmāh (lat 31°36' N., long 37°57' E.)

showed a phaneritic basalt with zoned plagioclase (andesine-labradorite), augite, commonly altered olivine, calcite, and black unidentified opaque minerals, probably ilmenite and magnetite. The thickest sequence of younger lava is at Umm Wu'āl (lat 31°49' N., long 38°53' E.) where about 100 m rests directly on the eroded Eocene surface. At other places younger basalt flows thinly cover Miocene and Pliocene undivided. This fact, coupled with the fact that little weathering is evident, has led to a considered Quaternary age for the upper Al Harrah volcanics.

Near the fort at Qurayyāt al Miḥ (lat 31°24' N., long 37°29' E.) there are about 35 m of older lava, a highly weathered alivine-bearing basalt, resting on Miocene and Pliocene marl. In the middle part of the succession, the lava is cut by numerous thin aplite dikes and at places an amygdaloidal phase is distinguished. In marked contrast to the younger basalts, the older lavas have been deeply weathered prior to deposition of an overlying sandstone that includes basalt boulders in the basal part. A few kilometers west of Qurayyāt al Miḥ similar lavas are interbedded with sandstone and marl of presumed Miocene and Pliocene age and here are considered to be of the same age.

CALCARBOUS DURICRUST

A resistant duricrust carapace masks underlying stratigraphic and structural details over some rather extensive areas in northwestern Arabia. Although the precise chemical conditions that produce this deposit are poorly understood, it is apparently a product of a somewhat more moist, possibly semiarid, climate than exists in present-day Arabia. During the dry season movement of ground water is upward to the surface where soluble substances are deposited. As evaporation proceeds, a caliche-like carbonate-enriched crust is built up, mainly of the material on which it forms. Where the underlying rock is carbonate, duricrust is particularly hard and in some instances supports escarpments as much as 50 m in height. If the underlying rock is sandstone, a much less resistant calcareous, gypsiferous, and earthy deposit forms.

Duricrust is particularly well developed on Paleozoic and Mesozoic units from Buraydah northwest to Al Widyān plateau, south of Al Jawf and Sakākāh, in Al Hūj, and on Tertiary beds south and west of the Saudi Arabia-Iraq Neutral Zone. Usually it is a discontinuous mantle of red, brown, gray, tan, and yellow, resistant, sandy limestone containing fragments of the underlying rock. Thickness of the crust ranges from a few centimeters to 3 or 4 m. Coarse frosted quartz grains are often present, and also a few fresh-water molluscs are present. In the southwestern Rub' al Khālī the few small patches of duricrust

known are gray to tan, locally gypsiferous, sandy limestone grading at places into sandstone with calcareous cement.

As duricrust is not known to have formed in rocks younger than Miocene and Pliocene, these carbonate-enriched rocks are believed to be Quaternary.

TERRACE, MUD FLAT, AND GYPSUM DEPOSITS

LAKE TERRACES

Lake beds, now cut into a steplike series of low terraces, crop out in the southwestern Rub' al Khālī around lat 19°05' N., long 46°20' E. and in the Shaqqat al Mi'ah (near lat 17°30' N., long 46°35' E.). These fresh-water sediments are interbedded, white, tan, and brown, fine-grained quartzose sandstone with micaceous, silty and rarely gypsiferous clay and fossiliferous silt.

A number of fragments of vertebrate teeth and bones were found within or associated with the lacustrine deposits. Age, based on these fossils, is considered to be late Pleistocene(?) to early Recent.

Elsewhere in the southwestern Rub' al Khālī, Paleolithic and Neolithic sites have yielded arrow heads, fist hatchets, scrapers, and other stone implements. At one locality charcoal, presumably from a Neolithic campsite, was dated by carbon-14 as 5,090 ± 200 years. Age was determined by T. A. Rafter (written commun., June 1960). Field (1958, 1960) has described the stone implements collected from these sites.

MARINE TERRACES AND RAISED BEACHES

Marine terraces and raised beaches are rather common along the western Persian Gulf shoreline. Within Saudi Arabia beach gravel and sand occurs on marine terraces and raised beaches from north of Al Jubayl (lat 27°01' N., long 49°40' E.) to the southern tip of Dawbat Salwah. The commonest occurrence of the marine Pleistocene is in the form of sand and coquina terraces 1 or 2 m above mean high tide. These terraces form low discontinuous mesas along the coastline and a short distance inland.

Along Dawbat Salwah well-preserved marine fossils, most of which are present-day species, are found in soft, pebbly sandstone and coquina. Maximum thickness of this fossiliferous unit is about 3 m. Quaternary marine fossils also occur at Sabkhat Sawdā' Nathil (lat 24°30' N., long 51°04' E.) about 3 m below mean high tide.

DELTAIC AND TIDAL MUD FLATS

Deposits of this type occur only in Kuwait and are described in connection with the surficial geology of that country.

GYPSUM DEPOSITS

Young bedded deposits of gypsum occur in small patches at several localities, usually in contact with

Miocene and Pliocene and with Quaternary units. Only one such deposit has been studied in sufficient detail to permit mapping, and this occurs south from Wādī al Fāw along the foot of the Al 'Arid escarpment. Here a thin, 60-km-long band of white to tan, powdery to patchy gypsum is associated with Quaternary gravel.

QUATERNARY DEPOSITS

TERRACE GRAVEL

Outcrops of terrace gravel are limited to two—one in the bottom of Wādī al Bāṭin where several small patches occur 60 and 90 km northeast of the Trans-Arabian Pipeline and another in Wādī as Sahbā' where a few isolated patches are present between the 47th and 48th meridians. The gravel is mainly limestone and quartz that has been concentrated in terrace deposits obviously related to present or recent drainage.

SHEET GRAVEL

The largest single occurrence of sheet gravel blankets the Ad Dibdibah plain—a broad, flat boulder-strewn surface flanking Al Bāṭin and extending from south of the Trans-Arabian Pipeline into Iraq and Kuwait. The sheet represents the residue of a vast flood of rock debris derived from the basement complex and funneling out through the Wādī ar Rimah-Al Bāṭin channel system. The gravel veneer is nowhere more than a single pebble thick and is chiefly quartz with varying proportions of carbonate, igneous, and metamorphic grains. The plains area around Tabūk is also littered with a similar gravel.

Another gravel sheet, the Aṣ Saḥn plain (around lat 30°40' N., long 42°40' E.), includes basalt pebbles probably derived from Al Harrah lava field. In addition, a large number of chert granules are included.

Large, coalescing, delta-like surfaces of outwash gravel emanate from the Wādī as Sahbā'-Wādī ad Dawāsir-Wādī Najrān drainage systems. Present distribution of exposures shows that prior to formation of the great Rub' al Khālī-Al Jāfūrah sand desert a vast part of the area—generally west of the 51st meridian—was blanketed by coarse rock debris pouring out from these channels. At the same time, large quantities of the debris were diverted (a short distance from the basement) along a shallow trough scooped in soft Permian beds, thus lining this depression with gravel from the vicinity of Wādī Najrān to Khuff (near lat 25°00' N.).

GRAVEL REMNANTS

Dissected remnants of gravel apparently unrelated to modern drainage occur in two areas: one along the foot of the Hit escarpment (between lats 24°20' N. and 24°32' N.) and the second in front of Al 'Aramah escarpment near lat 25°54' N. Grains are for the

most part limestone, but other rock types are included as well.

GRAVEL, SAND, AND SILT

Bottoms of channels and undrained depressions are commonly floored with a thin but often extensive layer of unconsolidated, locally derived sediment.

Gravel of this type represents: (1) a recent concentration of coarse debris from the immediately surrounding area, (2) a residual deposit derived from older sediment or rock by removal of intergranular fines, and (3) a lag concentrate from an earlier gravel sheet or train.

Numerous widely scattered, undrained basins have in common a flat, firm, silty surface that contrasts sharply with other crusty, brine-saturated depressions (Sabbkha deposits). The silt flats, known by various names depending on soil type, vegetation, and so forth, locally include caliche-like and gypsiferous deposits.

Other surficial deposits that cannot be subdivided or classified for any of several reasons include gravel, sand, silt, gypsum, and other associated fine material.

SABKHAH DEPOSITS

Sabbkha (plural: sibākḥ) is an Arabic term for coastal and inland saline flats or playas built up by deposition of silt, clay, and muddy sand in shallow, albeit sometimes extensive, depressions. The deposits are commonly saturated with brine and often are salt encrusted. Indeed, the presence of salt is the distinguishing feature of a sabbkha. Other silt-filled areas, usually centers of centripetal drainage, contain no salt. These are more correctly called Qī'ān.

Mamlāḥaḥ (plural: mamālīḥ), a name often heard in the interior, refers to a sabbkha where salt is, or at one time was, mined. Strictly speaking mamlāḥaḥ designates the excavation or area in the sabbkha where salt is being removed.

Sibākḥ are, for the most part, concentrated in a narrow belt along the coast from Kuwait to east of Qatar. Most are found within 60 km of the shoreline, but some are located far inland—for example, in Wādī as Sirḥān (at lat 30°50' N., long 38°10' E.), near Baq'ā' (lat 27°53' N., long 42°24' E.), southeast of Buraydah (lat 26°20' N., long 43°58' E.), near Al Qasab (lat 25°18' N., long 45°30' E.), around Yabrin (lat 23°17' N., long 48°56' E.), and over a wide band along the eastern margin of the Rub' al Khālī.

Origin of these saline flats is in doubt, but most workers now agree that they result from sand and silt, commonly eolian, infilling topographically low areas. Brine is nearly always to be found within 1 or 2 m of the surface. Apparently, prolonged evaporation of capillary water during dry periods concentrates and

precipitates various salts at and near the surface to form a hard saline crust. During moist periods, standing water from tidal invasion or runoff helps recharge the sediments and also by evaporation contributes to the salt scum.

EOLIAN SAND

Approximately one-half of the sedimentary area of Saudi Arabia is blanketed by eolian sand. The Rub' al Khālī contains probably the largest continuous body of sand in the world and covers nearly 600,000 sq km. Another 180,000 sq km is covered by interior nūfūds and Ad Dahna'. The largest of these, An Nafūd, is roughly 68,000 sq km.

R. A. Bramkamp developed a practical classification of the fundamental types of sand terrain found in Saudi Arabia. He recognized four main classes which were adopted and whose distribution was depicted on the Miscellaneous Geologic Investigations Map series. Basic characteristics of these classes are as follows:

- I. Transverse: Predominantly simple and compound barchan dunes in areas of more mobile sand and (or) simple rounded ridges, oriented transverse to the prevailing wind direction.
- II. Longitudinal: Primarily dīkākah (bush- or grass-covered sand) and various types of undulating sand sheets, in general characterized by elongation of the individual forms parallel to the prevailing wind direction, often partly stabilized by sparse vegetation.
- III. 'Urūq: Various forms of long, nearly parallel, sharp-crested narrow sand ridges and dune chains separated by broad sand valleys usually including elements of Type I sand terrain. These forms are the resultant of a system of two dominant wind directions and are identical to the saif dunes of north Africa.
- IV. Sand mountains: Dominated by large sand massifs commonly cresting 50 to 300 m above the substratum, often with superimposed dune patterns consisting of various types of complex barchans. Common forms are giant barchans spanning several kilometers from horn to horn, giant sigmoidal and pyramidal sand peaks as well as other less common peak forms, and giant oval to elongate sand mounds.

STRUCTURE

GENERAL FEATURES

The structural pattern of the Arabian Peninsula was set in Precambrian time with stabilization of the Arabian shield. These ancient rocks, now lying in tangled confusion, in themselves reveal a complex and mobile history. By the outset of the Paleozoic Era, however, they had been fused into a rigid land mass, and their surface had been reduced to a nearly level plain.

From the Cambrian on, vast epicontinental seas moved back and forth across the lower parts of this stable basement core and there deposited a comparatively thin succession of almost flat-lying strata. The epicontinental seas were in turn flanked on the north and east by a great sedimentary basin—the Tethyan trough—that occupied a relatively constant area in Turkey, northern Iraq, and southwestern Iran. The trough remained a negative feature throughout most of the Paleozoic and Mesozoic while many thousands of feet of sediment accumulated. Destruction of the ancient seaway began in the Late Cretaceous with orogenic movement recorded from Turkey through Iran and extending into Oman. The climax came, however, in the late Tertiary (*Alpine orogeny*) when rocks from the deeper part of the basin were folded and thrust to form the Zagros-Taurus chain of mountains. It is during this period that the great rift-fault systems of Africa and the Red Sea area also began to take on their present form, although movement on these faults may have started somewhat earlier.

Within this broad tectonic framework, two major structural provinces are recognized (pl. 2). One is the comparatively stable interior region whose rigidity is controlled by Precambrian basement. The exposed part of the shield, as well as that part thinly veneered with little-disturbed shelf sediment, make up this province. The other major province is the great mobile belt peripheral to the stable region and made up of the Taurus-Zagros-Oman Mountain systems.

Saudi Arabia falls wholly within the stable region, and it is this structural province with which we are most concerned here. Consequently, this province and its significant structural subdivisions will be discussed in some detail; those peripheral to it will be touched on but briefly. It should be emphasized that stable is a relative term used here to differentiate an area that has from Precambrian to Recent time been subjected mainly to gentle warping and tilting.

STABLE REGION ARABIAN SHIELD

Shield rocks, comparatively stable and primarily positive since Precambrian time, make up a sizable part of the Arabian Peninsula. On the west they form most of Najd and all of Al Hijāz and 'Asir; on the southwest they support the highlands of Yemen, and along the southern coast of the Arabian Peninsula they can be seen in sporadic outcrops. Until recently, the Arabian Shield was a projection of the shield of Africa but is now separated from it by Red Sea rifting.

WESTERN ARABIAN SHIELD

The western Arabian Shield is an extensive area of Precambrian rocks, mainly igneous and metamorphic,

and largely overlain by younger volcanics in the west. Though the shield has acted as a rigid land mass since the beginning of Cambrian time, consolidation was long in coming. Included within the basement complex are great belts of sedimentary rocks—now contorted, intruded, and metamorphosed—that record the growth and decay of former mountain systems. Presumably, through the eras of Precambrian time, the shield was subjected not once but several times to downwarping, sedimentation, orogeny, injection by plutonic rocks, and leveling before becoming immobile—a complex, but little known, structural history comparable with that of other shields and former geosynclinal areas.

Likewise, the structural situation after the start of the Paleozoic is obscure, but some intrusion and local faulting is likely. A number of epirogenic movements of the shield have been clearly recorded in the sedimentary sequence, generally in the form of regional unconformities. During the Tertiary Period, substantial faulting and other disturbances occurred along the margin of the Red Sea depression.

YEMEN-WESTERN ADEN PLATEAU

In the Yemen-Western Aden area, Precambrian basement supports a relatively high, substantially faulted plateau. The plateau is capped in northern Yemen by patches of flat-lying Jurassic, Cretaceous, and Tertiary sedimentary rocks. Massive extrusive volcanic rocks of Late Cretaceous to Recent age cover central and southern Yemen and enclose fault blocks of basement and Mesozoic rocks that have been uplifted through the volcanic sheet. Less stable than the western and southern part of the Arabian Shield, the plateau area apparently operated as a hinge, absorbing differential movement between flanking massifs. Presumably, Yemen-Western Aden remained positive until the late Jurassic and then, for the first time, was sufficiently downwarped to permit direct communication between the Tethyan and east African seaways.

SOUTHERN ARABIAN SHIELD

The structure and configuration of the southern Arabian Shield is obscured by the Gulf of Aden; however, its northern margin can be roughly reconstructed from exposures preserved along the Hadramawt, Al Mahrah, and Dhufar coasts and in the Khuriya Muriya Islands. Like other parts of the Arabian Shield, these rocks show evidence of strong deformation, intrusion, and metamorphism followed by mature peneplanation before the first sediments were deposited.

ARABIAN SHIELD

After solidification and mature peneplanation, the Arabian Shield was tilted slightly northeast toward

the ancestral Tethys trough. As subsidence continued, shallow seas advanced across the beveled surface of crystalline rocks and buried it beneath thin sheets of almost flat-lying sediment. It is this belt of low-dipping, relatively undisturbed beds that gives rise to the second main structural province of the stable region—the Arabian Shelf. It should be kept in mind that the shelf differs from the exposed part of the shield only in possessing a thin sedimentary cover.

As early as Early Ordovician, marine water had transgressed inland nearly to the present limit of sedimentary beds, well documenting the invasion with a thin but widespread, graptolite-rich shale. Consequent upon successive rising and sinking of the shield, seas advanced and retreated. Because the sea floor was so flat, even gentle bending substantially moved the shoreline and altered the position of land and sea. Effects of such epeirogenic movements, clearly recorded in the interior by unconformities, disconformities, and alternating marine-nonmarine rocks, fade as the deeper part of the basin is approached. Here, subsidence apparently persisted with few interruptions from Paleozoic to relatively recent time.

Sediments of the shelf are characteristically of shallow-water origin. Limestone, elastic-textured and mechanically sorted, is the most striking rock type. Sandstone and shale are also present in large amount. All units, regardless of lithology, are usually thin and widespread, maintaining lithologic character over large areas. Shifts in facies do occur, but these are usually gradual. Such lithologic constancy, presumably brought about by continued sorting and reworking of the limited amount of sediment introduced into the basin, reflects prolonged stability.

Not all parts of the Arabian Shelf had the same geologic history. Some areas were more active than others; some were depressed and some elevated either persistently or for short periods. Thus the shelf is divisible into several subprovinces—namely, an Interior Homocline everywhere marginal to the shield, an Interior Platform bordering the homocline, and, adjacent to the platform, several basinal areas that have from time to time collected thicker deposits. In connection with this, the Interior Platform and adjacent basins correspond at least in a rough way to the “unstable shelf” just as the Interior Homocline appears to represent the “stable shelf.”

INTERIOR HOMOCLINE

Bordering the shield is a belt of Paleozoic, Mesozoic, and Cenozoic strata whose dip basinward is so slight and uniform as to be imperceptible to the eye. Plane-table, structure drill, and seismograph surveys over the area have defined a remarkably constant homocline

with an average width of about 400 km and a persistent dip ranging from slightly more than 1°00' in the Permian and Triassic to 0°20' in Upper Cretaceous and Eocene beds.

The homocline thus defined marks an area of unusual tectonic stability. To be sure, significant structural interruptions do occur, but these appear to result from blocks of different sizes and shapes moving independently and without disturbing adjacent parts of the homoclinal surface. Change in strike of the homocline, related to gentle flexing of the basement, tends to break the belt into several poorly defined segments.

CENTRAL ARABIAN ARCH—DEFINED BY NORTHERN AND SOUTHERN TUWAYQ SEGMENTS

One structural feature—the central Arabian arch—has had a profound influence on the present surface distribution of sedimentary rocks. The name applies to the area of changing strike between the northern Tuwayq and southern Tuwayq segments of the Interior Homocline. In reality, these segments are an integral part of the arch which affects all rocks from the basement up; its influence can still be seen as far east as Qatar. The arch, although a very gentle feature, appears to have considerable importance by marking the area of maximum curvature of the Interior Homocline in central Arabia and by supporting the reversal between the north-dipping part of the shelf and its south-dipping part which passes uniformly under the Rub' al Khālī.

Early work in Arabia led to the assumption that this great basement ridge was an ancient and permanent positive feature. It was assumed that bands of sedimentary rock were deposited around this swell in much their present form and original strike of deposition roughly paralleled present strike. Furthermore, it was assumed that the structural form of eastern Arabia was due to regional and uniform tilting of the shield toward the Persian Gulf and Rub' al Khālī basins. Sediment distribution and geometry of rock units around the arch have shown this concept to be incorrect, and it is now known that the history of the feature is much more complex.

During early Paleozoic time, the arch was mildly positive, as pre-Permian units seem to pinch out against it. Strong upwarping occurred in the later part of the Paleozoic Era (post-Early Devonian and pre-Late Permian), older beds were beveled and stripped from the crest of the arch, and later submergence permitted deposition of Upper Permian carbonates directly on basement across the axis and for some distance north and south.

During Mesozoic time, the central part of the craton gradually subsided, and thick sequences of continental

and shallow marine sediments accumulated in a basin whose deepest part apparently fell roughly along the present axis of the arch. This relationship is particularly marked in the Jurassic but can also be seen in the rocks of bracketing systems. Detailed measurements show that the Jurassic is thickest on or near the axis of the arch and thins uniformly and persistently to the north and south. Pre-Wasia (Middle Cretaceous) truncation accounts for some of the thinning in the far north, but not all, for the section is distinctly condensed when compared with an equivalent sequence near the center of the arch. There is also a corresponding change from deeper water to shallow water and even continental sediments away from the axis. Thick intervals of limestone and shale in the high area are represented by shale and sandstone on the flanks. It seems logical to assume from these data that the shoreline of Jurassic times in central Arabia fell considerably west of the present outcrop belt and lay approximately along a line connecting Jurassic exposures on the north and south where an approach to strand-line conditions is evident.

The first traces in the sedimentary record which would indicate the origin of the central Arabian arch appear in the Wasia Formation (Middle Cretaceous). On outcrop, this formation is continental in the south where it disconformably overlies nonmarine rocks of Early Cretaceous age. On and north of the arch, however, Wasia rocks become progressively more marine and sharply transgress older strata. The best explanation of this change appears to be that the sagging, which resulted in thickened Jurassic and Lower Cretaceous deposits, was disrupted during pre-Wasia deformation with the uplift of the southern part of Arabia. At the same time, subsidence continued in the north. Thus, in contrast to the relatively stable conditions that prevailed in the southern Tuwayq area, the northern Tuwayq segment and adjacent parts of the shelf were sites of active depression. In general, the zone which separates these two areas coincides fairly well with the central Arabian arch. It is therefore considered that the arch results from its position between a stable or slightly rising province and a gradually sinking area, giving rise to a gentle swell.

During Aruma (Upper Cretaceous) time, this same general pattern of movement persisted, and the structural elements inherited from the Middle Cretaceous were still further emphasized. The southern Tuwayq-southwestern Rub' al Khālī area remained emergent, and marine rocks were excluded. Continued subsidence in the north, quite possibly at an accelerated rate, can be assumed from a thickened rock sequence and a sharp change in strike of the

Interior Homocline during Late Cretaceous time. Details of this shift in strike are discussed in connection with the formation of the Hā'il arch.

Subsidence in the north continued while Paleocene and Eocene rocks were deposited, thus further increasing the apparent relief of the arch. The Tertiary picture is complicated by the fact that the Rub' al Khālī became an area of active subsidence for the first time. Downwarping here would also tend to accentuate the basement ridge. It is this differential sag, in fact, that may be in large part responsible for the central Arabian arch, probably a residual high between the periodically subsiding Persian Gulf and Rub' al Khālī basins rather than a true independent positive feature.

It is doubtful that the central Arabian arch was further exaggerated in Miocene and later time, though there is a reflection of the swell in the arc of the Ṣumman terrace. Miocene sediments of the Ṣumman are exclusively continental, however, and as such would be much influenced by adjacent topography during their deposition. At this time the topography, even as it does today, must have shown the influence of the arch, which would exercise a primary control on the drainage as well as on the form of the surface on which the Miocene was laid down.

Support for this concept of the formation of the central Arabian arch comes from the presence of the Wādī Nisāb-Wādī as Sahbā' graben and trough complex along the axis of the swell. From a regional point of view, these tensional structural features form but a small part of a major system of grabens that, near the western edge of the Tuwayq Mountains, swings northwest in a great arc along the Tuwayq front and then again passes through the Tuwayq escarpments west of Al Majma' ah. The counterpart of the central Arabian graben and trough system can be seen far to the northwest as the Khawr Umm Wu' al graben and the plexus of faults around Al Jawf-Sakākah. Thus, these tensional features are found about in the place they would be expected if the central Arabian arch formed in the manner outlined above; that is, the faults mark the area of maximum tension along a hinge line between a stable upland block and a sinking shelf. Similarly, the age of the graben system fits well into this general concept in that it appears to have originated in mid- or Late Cretaceous time and shows evidence of continued movement during the Paleocene and Eocene.

HĀ'IL ARCH

A shift in strike of the Interior Homocline around Hā'il (lat 27°32' N., long 41°43' E.) defines the Hā'il arch, a structural feature similar to the central Arabian arch. Lower Paleozoic sedimentary rocks, which have a consistent regional strike of N. 45° W. in the northern

Tuwayq segment of the Interior Homocline, swing gradually west in conformity with the trend of the underlying basement. At Jibāl at Tawāl, about 40 km north of Hā'il, a uniform strike of N. 70° W. was measured in Ordovician shale. In all probability the strike continues to parallel the basement margin, shifting first to west and then west-southwest to define the west flank of the arch, although evidence for this is hidden by An Nafūd sand.

Lack of significant change in facies or thickness of sedimentary units suggests that the arch was merely a stable headland around which Paleozoic and later seas advanced. The first definite sign of movement comes in the Cretaceous Period. Middle Cretaceous rocks, in sandstone facies, were deposited uninterruptedly across the crest of the arch, essentially parallel to the strike of the Paleozoic strata. On the other hand, basal Aruma (Upper Cretaceous) rocks show sharp facies change from marine carbonate on the east flank of the swell to continental sandstone across the crest. These beds were the last to be deposited over the arch before the strike of the Interior Homocline was shifted north into Iraq by the rising basement.

Surface mapping north of An Nafūd detected the prolongation of the Hā'il arch where it is a broad swell in Cretaceous and Eocene limestone, the high part passing east of Jabal 'Unāzah on the Saudi Arabia-Iraq boundary. The northeast flank dips gradually toward Iraq; the southwest flank passes gently into the Sirbān-Turayf basin. At the crest of the arch is Khawr Umm Wu'al, a trough made up of a series of grabens and synclinal depressions. Its relationship to the Hā'il arch approximates the relationship between the Wādī Nisāb-Wādī as Salihā grabens and the central Arabian arch.

Structure drilling near the Trans-Arabian Pipeline also confirms the presence of the Hā'il arch at depth and has given a relatively complete transverse section of a broad arch between Badanah and Turayf, its highest point being roughly 40 km west of Al Jalāmīd (lat 31°19' N., long 40°03' E.). Upper Cretaceous and Eocene strata thicken and apparently represent a more complete rock sequence in both directions away from the crest. The swell is also present in the older, underlying, presumable Paleozoic rocks.

The Hā'il arch no doubt continues northward into Iraq and there joins with the Rutbah high. Information is too incomplete to precisely define the axis of the arch, but it apparently passes west of Hā'il, through the Al Jawf-Sakākah area, west of Al Jalāmīd, and east of Jabal 'Unāzah. The arch may have originated by its own growth or as a residual high flanked by one or possibly two areas of subsidence. In either event,

the time of its formation appears to have been mainly Cretaceous and early Tertiary.

One significant aspect of the Hā'il arch is that all major faults in the area conform to a definite northwest-southeast trend. This trend may be related to persistent Late Cretaceous and Eocene sinking of the Persian Gulf and Sirbān-Turayf basins, which caused tensional faulting of the residual high between. The rise of the Hā'il arch had a profound effect on the architecture of the Tethys seaway. Prior to appearance of the arch, strike of Paleozoic, and presumably most Mesozoic units as well, closely paralleled the northern margin of the shield. With uplift of the arch in the Cretaceous, communication across northwestern Arabia between the Persian Gulf and Mediterranean seaways was broken. Consequent upon this, the Interior Homocline was split into two segments—to the west the Tabūk segment comprised mainly of Paleozoic rocks and to the east the Widyān basin margin made up solely of Cretaceous and younger beds.

WIDYĀN BASIN MARGIN

The Widyān basin is the Saudi Arabian part of a major basin of deposition. As used here, however, the name is applied to the eastern limb of the Hā'il-Rutbah swell. It is an area of Upper Cretaceous and Eocene rocks having a gentle northeast dip averaging about 2.5 m per km.

Superimposed on the broad homoclinal framework are a great many of minor irregularities. These are primarily solution-collapse features of various types, covering a wide range of radius and amplitude—from sinks and residual highs a few tens of meters across and 5 to 10 m in height to features several kilometers in diameter and 10 to 20 m or more in height. The size of individual structures in any given area usually falls within a relatively restricted range, as the characteristics of the slumping are presumably determined by the depth of the soluble unit whose removal has caused the collapse.

Larger structural features are surprisingly few, and in fact, only in the far southwestern part of the province can it be shown conclusively that faulting, originating from deep-seated causes, follows the trend of the Al Jawf area with only minor displacement and disturbance of Upper Cretaceous rocks. Evidence to the west suggests much larger displacements along these trends in pre-Upper Cretaceous units.

The characteristics and formation of long curved monoclines such as Jāl al Baṭn and Jāl Nawāzīr have been previously discussed in connection with the Umm er Radhuma Formation (p. 84).

The Widyān basin margin is a northwestern extension of the Interior Homocline, although it shows a certain

amount of sinuosity. In broad plan, strike of Cretaceous and Paleocene beds shifts from slightly west of north near the Saudi Arabia-Iraq boundary to N. 60° W. at Darb Zubaydah (long 43°25' E.). Southward, the strike reverses to about N. 40° W., and the beds of Al Widyān merge with the northern Tuwayq segment of the Interior Homocline.

HADRAMAWT PLATEAU

Between the southern Arabian Shield and the sands of the Rub' al Khālī is a high, dissected, generally northward-dipping plateau of early Tertiary rocks which forms the southern margin of the Rub' al Khālī basin. Basically, the plateau is a broad, generally east-west-trending swell extending nearly from the 47th meridian to Dhufar. Superimposed on the main swell are two smaller east-west arches separated by a low syncline, the western end of which roughly corresponds with the deep channel of Wādī Hadramawt.

The area has been affected by some east-west faulting. Such disturbances are relatively minor in the main plateau area but are more pronounced along the coast where they give rise to a rugged fault-block topography.

HADRAMAWT SEGMENT

North of the Hadramawt Plateau and extending east to Oman is the lower part of the Interior Homocline—the Hadramawt segment. Much of the segment is buried beneath the Rub' al Khālī where structure drill and seismograph have mapped uniform north dip and defined the northern toe. Average dip of Tertiary and Quaternary rocks is about 0°20'. Underlying Mesozoic strata have a more pronounced dip owing to thinning and probable truncation toward the Hadramawt Plateau.

East of long 48°, strike of the homocline holds relatively constant at slightly north of east. West of this meridian, however, strike swings rapidly west and then northwest to define the southern limb of a broad, northeastward-plunging syncline which connects the Hadramawt segment of the Interior Homocline with the southern Tuwayq segment. This bend, which in effect outlines the southwestern margin of the Rub' al Khālī basin, involves a change in strike of about 120°. Presumably, this area of maximum curvature also corresponds to a hinge line or zone of adjustment between the western Arabian and southern Arabian Shields.

INTERIOR PLATFORM

Bordering the homocline is the Interior Platform, an area of varying width in which systematic dip off the crystalline core no longer prevails. The nearly flat structural platform is sharply set off from the homocline by an abrupt break in slope—a hinge line between the two structural provinces. The opposite edge of the

platform is less well defined, trending southeast from Kuwait into the Persian Gulf, far out around Qatar and possibly (in one area north of Qatar) reaching east as far as the coast of Iran, and passing inland along the western edge of Sabkhat Matī and around the Rub' al Khālī basin before terminating against the Oman Mountains near lat 23° N., long 56° E. Width of the platform ranges from about 100 km along the southern and western sides of the Rub' al Khālī basin to 400 km or more across the Qatar Peninsula. The great width of the platform in the vicinity of Qatar could conceivably reflect the extension of the central Arabian arch.

The deep structure of the sedimentary rocks of the platform must be inferred from structure drill and seismic results. These data indicate that the beds are unusually flat in a geological sense and irregularities are limited to low, gentle structural undulations that lack any strong orientation. Superimposed on this are several major north-south anticlinal axes that rise above the general level of the platform. One of the most notable of these is the En Nala anticline, the southern part of which includes the oil field of Ghawar. The folds of Abqaiq and Qatif are other good examples of large north-south trends. The surviving segments of the platform on the two sides of any of these major axes seem to have about the same structural elevation.

Any conclusions are highly speculative, but the flat, gently undulating parts of the structural platform are presumed to be underlain by rigid blocks of basement that resisted deformation, thus protecting the sedimentary blanket from significant disturbance. The origin of the major anticlines is still obscure, but if local complexities are disregarded, the nearly flat crest and steep linear flanks give strong reason to suspect that these features are related to some sort of horstlike uplift at great depth. Study of gravity data further strengthens this hypothesis. Several concepts of causal stresses seem equally acceptable—simple compression, deep-seated differential uplift, and horizontal torsion.

Only one sharp feature—Dammam Dome—departs completely from some expression of north-south elongation. Because of its complex crestal faulting, strong negative gravity anomaly, and oval shape, it is regarded as a salt-intrusion structure.

BASINS

Several depressions are superimposed on the Arabian Shelf and at one time or another have received thick deposits relative to adjacent parts of the platform. Such basinal sags have formed in the northeastern Rub' al Khālī, northern Persian Gulf, Dibdibah, and Sirbān-Turayf areas.

RUB' AL KHĀLĪ BASIN

Seismograph and structure drill work in the Rub'

al Khālī have outlined an elongate basin that plunges gently northeast toward Bi'r Hādī (lat 19°26' N., long 51°02' E.) toward the Persian Gulf. The northeastern part of the trough apparently extends across Abu Dhabi and Trucial Oman and continues into the Persian Gulf almost as far as the coast of Iran. Width of the basin is relatively uniform throughout its length, averaging about 300 km.

The Rub' al Khālī basin is primarily a Tertiary feature. Paleocene, lower and middle Eocene, and upper Tertiary sedimentary rocks thicken toward the center. This thickening is moderate, however, except in the eastern part of Trucial Oman where very thick Tertiary deposition took place in the deep sedimentary trough in front of the intensely folded Oman ranges.

Mesozoic rocks show a trend toward shallower water sedimentation from the center of the basin northwest, west, and southwest toward the platform. A similar trend appears to the south and southeast although much of the pertinent evidence for this has been eliminated by several Mesozoic unconformities. To the northeast, deposition appears to have taken place in as deep or deeper water than in the central Rub' al Khālī. In general, Mesozoic sedimentation appears to be related to a basinal area much larger than the present depression. If this is true, the Rub' al Khālī as an independent basin would be exclusively Tertiary, possibly with some Late Cretaceous history. Apparently, the basin is a shallow reflection of the depressed hinge between opposing basement blocks.

NORTHERN PERSIAN GULF BASIN

Limited marine seismic work and regional relationships show that a structurally low area covers the head of the Persian Gulf. Seismic mapping has provided some clue to the geometry of the higher part of its southwest flank which dips at a nearly constant 2° to 4° NE., a steep dip, indeed, when compared to the adjacent platform and the gentle gradient (0°20' to 1°20') of the Interior Homocline. The northeastern margin of the basin is formed by the Zagros Mountain foreland.

DIBDIBA BASIN

The term Dibdiba basin is applied to a downwarped area between the Jauf-Wafra-Burgan high and the Interior Homocline. The basin, postulated primarily on seismic work which indicates a major thickness of Cretaceous rocks, extends north between the Neutral Zones into southern Iraq.

SIRHĀN-TURAYF BASIN

Structure drilling and surface mapping have delineated in the northwestern corner of Saudi Arabia a synclinal basin filled with a thick sequence of Upper

Cretaceous and Eocene sediments. The basin opens to the north and northwest into Jordan. Volcanic rocks, representing the southern end of the major lava fields of the Syrian desert, blanket a substantial area along the low part of the trough. Small linear faults with a north-northwest trend probably reflecting dislocation in older rocks are common. One structural trough-graben (Khawr Umm Wu'āl) occurs in the eastern part of the area.

The southwest flank of the Sirhān-Turayf basin is relatively complex and may even represent a half graben that controls the present course of Wādī as Sirhān. The Sirhān depression, a broad elongate trough, is flanked on the southwest by a uniformly northeast-dipping homocline that is also the southwest flank of the much larger Sirhān-Turayf basin. A series of normal faults, downthrown to the southwest and largely buried under a mass of extrusive basalts, bound the Sirhān depression on the northeast.

The Sirhān-Turayf basin may have resulted from growth of the Hā'il arch to the east during Late Cretaceous and Eocene time. A more likely explanation, however, is that the basin developed as a sag in a structurally flat area. This interpretation is suggested by comparable elevations of contemporaneous rocks on the two sides of the basin.

Later structural deformation of the basin shows a dominance of tensional over compressional forces—abundance of faults and grabens and rarity of folds. No thrust faults are recognized.

MOBILE BELT—MOUNTAINS AND FORELANDS

Encircling the stable interior region is a mobile belt of young mountains and a thin foreland area deformed contemporaneously with the main ranges. The various ranges butting against the Arabian shelf—the Zagros of Iran and the Oman Mountains—are small links in the much longer Alpine-Himalayan system. None fall within Saudi Arabia, and only a brief description of them will be given here.

MOUNTAINS ZAGROS MOUNTAINS

The Iranian Ranges or Zagros Mountains, the term usually used for the whole mountain belt of southwestern Iran, is a broad belt of northwest-southeast folded and faulted Paleozoic, Mesozoic and Cenozoic rocks. Thrusting is common in the younger sediments. Evidence for some tectonic activity is present in Upper Cretaceous rocks, but the main orogenic movements occurred in late Tertiary, mainly Pliocene time.

OMAN MOUNTAINS

Bordering the Gulf of Oman on the southwest is a complex geanticline of Paleozoic and Mesozoic rocks

with Cenozoic sediments overlapping the flanks. Orogenic movements began at the end of mid-Cretaceous time and reoccurred between the Oligocene and Miocene.

FORELANDS

ZAGROS MOUNTAINS FORELAND

Southwest of the Zagros Mountains proper is a thin belt of gently folded rocks. Structural features within this foreland area are generally elongate, symmetrical, and are parallel and contemporaneous with the main ranges.

OMAN MOUNTAINS FORELAND

An area of gently deformed, generally west-dipping Mesozoic rocks almost entirely covered by flat-lying Tertiary sediments flank the Oman Mountains. Their formation, but to a lesser degree, resulted from the same orogenic forces which affected the Oman Mountains.

HUQF-HAUSHI SWELL

In southeastern Oman, near the coast, is a broad, gently uplifted feature—the Huqf-Hausshi swell. The swell, built around a block-faulted core of Paleozoic rocks, trends north-northeast and is terminated on the west by a gently dipping scarp that exposes Mesozoic and Tertiary rocks. Paleozoic, Mesozoic, and Tertiary deposits unconformably lap over the flanks of the ancient high.

CENTRAL ARABIAN GRABEN AND TROUGH SYSTEM

A notable feature of the Interior Homocline is the central Arabian graben and trough system. This system is a series of grabens and synclinal depressions forming a broad arc concave to the northeast and extending west from Harāḍ through Ad Dahna', Al Kharj, and Durrā, swinging nearly parallel to the Tuwayq front for some distance, and finally passing back through Jabal Tuwayq a short distance west of Al Majma'ah. The system is actually a compound feature in which the progressive tensional readjustments are passed from one graben to another en echelon. In some cases this passage between adjacent grabens takes place by scissors faulting and oblique synclinal folds. Six major grabens, two large troughs, and numerous small subsidiary grabens and troughs are related to this structural system which can be traced for at least 560 km.

NIṢĀḤ GRABEN

A well-defined graben coincides over much of its length with the present valley of Wādī Niṣāḥ. The structure has been traced eastward with few interruptions from the western edge of Jabal Tuwayq to long 47°10' E., a distance of nearly 90 km.

The Niṣāḥ graben, a linear feature generally trending N. 85° W. and ranging in width from 2.0 to 3.7 km, is

bounded on the north and south by normal faults which dip under the down-dropped floor at 60° to 70°. Displacement on the Niṣāḥ border faults is hard to determine in the eastern part of the trough where the picture is obscured on both sides by the badly slumped Arab and Sulayī sequence. It is obvious, however, that movement has been at least 100 m and possibly as much as 300 m as Biyahd and Wasia rocks in the floor of the graben are in contact with Arab, Sulayī and Yamama beds across the faults.

In the western part of the trough, the amount of displacement can be more accurately determined. Here, lower Arab is downthrown against Hanifa, and upper Hanifa can be seen dropped down against upper Dhurma, which suggests between 200 and 300 m of movement. In addition to the two main boundary faults, the floor of the graben is broken by subsidiary faults, satisfactory exposures of which occur only in a few places.

Drag effects are found in rocks on both sides of the graben. This sagging is visible as far as 1 km back from the edge of the trough. In addition to this broad, rather gentle drape, local intense drag is found in the immediate vicinity of the fault planes.

Seemingly, the first beds displaced are of Wasia (Middle Cretaceous) age. The Wasia preserved far west in the graben, however, might conceivably represent a tongue of sediment deposited in a trough already in existence before Wasia deposition began. This concept of pre-Wasia movement is seriously challenged by one feature—that is, the complete lack of limestone debris in Wasia rocks flooring Wādī Niṣāḥ. Presumably the upthrown sides of the graben would have shed considerable limestone fragments into the down-dropped trough. Such is not the case, however. Thus on present evidence it is considered likely that graben formation began sometime after the close of Wasia deposition.

The closing age of Niṣāḥ movement cannot be fixed directly; however, Eocene rocks are involved in the formation of the Sahbā' trough, a direct extension of the Niṣāḥ graben. Thus, some movement probably took place on the Niṣāḥ faults as late as the Eocene.

SAHBĀ' TROUGH

Wādī as Sahbā', although a much broader feature, is a direct eastward extension of Wādī Niṣāḥ and the Niṣāḥ graben. The great width of Wādī as Sahbā', particularly in its upper part west of As Salamiyah (long 47°18' E.), results in an extensive area of cover that obscures the underlying structure. Exposures improve along the wādī margin to the east where the opposite flanks are formed by single monoclinical flexures dipping toward the center of the trough. A significant

feature of this area is that Upper Cretaceous and Paleocene rocks are exposed along the north side of the trough; on the south side corresponding units are sharply offset and appear much further east.

The Sahbā' trough continues in much the same form through Ad Dahnā' to a point just west of ab Harāḍ, thence trends southeast until it is lost in Quaternary sand and gravel. In Miocene and Pliocene rocks the trough is barely discernible. This eastward attenuation is apparent in lower and middle Eocene strata which show only limited sagging. This condition could result from a gradual dying out of the trough to the east or could indicate that most of the downwarping occurred before these rocks were deposited.

MUGHRAH STRUCTURAL TROUGH

The Mughrah trough is a subsidiary structural sag which roughly parallels the Sahbā' trough on the north and has been traced more than 40 km from Wādī Wasi' (long 47°43' E.) nearly to the Riyadh-Al Kharj road where it is lost in the Arab-Hith solution-collapse zone. The apparent continuation of the trough, although substantially offset to the north, appears again in front of the Hit escarpment and can be traced westward more than 35 km.

As seen in the western Mughrah hills, the trough is a low, broad syncline. Flank dips are gentle, usually less than 10°. The eastern part of the trough apparently maintains continuity to where it merges with the Sahbā' trough south of 'Ayn Wasi'. The trough plunges gently east until finally Eocene rocks are present along the axis. Eocene appears south of 'Ayn Wasi' and extends some distance west along the floor of the trough. Near the Riyadh-Al Kharj road, undeformed fresh-water beds presumably of Miocene and Pliocene age cross the projection of the trough, suggesting either that the sag dies out immediately to the east or that it antedates the fresh-water rocks. From this evidence, the age of the trough is considered as post-Eocene and pre-Miocene.

An interesting aspect of the Mughrah trough is the presence along its axis of a well-defined band of channel gravels. These gravels represent the deposits of a stream whose course was determined by the trough and have since been dissected by more recent transverse drainage.

AWSAT GRABEN

Another graben—the Awsat—has been mapped north and northwest of the western part of Wādī Nisāb. The Awsat graben branches off from Wādī Nisāb and extends almost 90 km northwest terminating at Khashm Zabīm (lat 24°32' N., long 45°59' E.). Throughout this distance strike of the graben varies little from N.

68° W. East of the main Tuwayq escarpment, the Awsat graben is a deep trough sharply incised in the upland limestone surfaces. Alluvial fill, except in a few places, obscures outcrops in the floor of the trough. West of the main Tuwayq escarpment, however, the graben is preserved as isolated outliers of Dhurma and Marrat rocks.

Instead of a simple valley graben, the Awsat structure is composed of two overlapping en echelon segments. The eastern segment disappears near long 46°30' E. The western segment starts about 7 km east of this meridian, and for this distance the two troughs share a common boundary fault. The borders or the grabens are formed by high-angle faults with drag folds and occasional auxiliary faults.

Displacement along graben faults ranges from 50 to 300 m. The youngest formation involved in the faulting is Jubaila Limestone which appears to be faulted down against the Tuwayq Mountain Limestone.

DURMA GRABEN

A third graben—the Dūrmā graben—about 12 km north and nearly parallel to the Awsat graben, is more than 50 km in length, from 1 to 2 km wide, and trends about N. 68° W. from the entrance of Sha'tb Hā' to Khashm Mijbarah (lat 24°35' N., long 46°03' E.).

Most of the Dūrmā graben is characteristically expressed as a sharp limestone ridge now broken into several segments by erratically spaced erosional gaps. Like the western part of Awsat graben, these ridges are bounded by obsequent faultline scarps. The faults are simple, high-angle, and normal, occasional splinter faults occurring within the graben. Margins of the trough are commonly warped as if by the influence of drag.

Differential relief on the limestone ridge reaches a maximum at Khashm Mijbarah where the sharp spine of limestone rises more than 120 m above the surrounding silt flats. Southeastward, the ridge becomes lower and gaps more frequent. Near the main Tuwayq cliff only small hills of limestone remain. As the graben approaches the entrance of Sha'tb Hā', the Tuwayq Mountain Limestone escarpment converges upon it, and the margins of the down-dropped limestone blocks coincide with the walls of the canyon breaking through the Tuwayq front. Beyond this point the graben is expressed as a sharp fault trough.

Displacement of beds in the Dūrmā graben ranges from a few meters in the southeast to more than 300 m at Khashm Mijbarah. In the pass, south of the town of Dūrmā, lower Hanifa strata are downthrown against the lower Dhurma. The stratigraphic interval involved suggests a displacement of 400 m or more.

QARĀDĀN GRABEN

The Qarādān structure begins a few kilometers north of Khashm Mijjarah and extends about 18 km N. 50° W. to Khashm Qarādān (lat 24°44' N., long 45°54' E.). This feature was formerly considered to be a northwestern continuation of the Durrā graben but is now known to be separated from it by transverse faults with a strike of about N. 70° W. If it were not for these transverse dislocations, the Qarādān graben might be interpreted as an extension or an en echelon part of the Durrā structure.

Qarādān graben, like the Durrā, consists of an elongate, flat-topped, frequently breached limestone ridge with a relief of between 50 and 100 m. The flanks of the block are made up of a series of overlapping alluvial fans which cover the bounding faults for nearly the full length of the graben. Several low passes which appear to be synclinal sags break through the ridge of limestone.

Only the Tuwaiq Mountain Limestone is preserved in Qarādān graben. At the northeastern end of the trough this limestone is dropped beside the uppermost beds of the Marrat Formation, a relationship that shows 400 m or more of displacement.

BARRAH GRABEN

The general outline of another graben can be reconstructed around a resistant limestone ridge cropping out about 25 km northwest of Khashm Qarādān. A prominent outlier of Tuwaiq Mountain Limestone, Naṣīlat az Zu'aynah (lat 24°56' N., long 45°48' E.), marks the southeastern end of the ridge. The graben as identified from the block of limestone is 16 km long, averages a little more than 2 km in width, and bears N. 55° W. Its topographic expression is that of a series of deeply dissected limestone ridges separated by several passes which may be synclinal in origin. Erosion of the limestone is much more complete than in other grabens so far described. Topographic relief does not exceed 75 m.

Faults bordering the limestone ridge are covered by coalescing alluvial fans, and their location can only be inferred by the topography. The structure is a down-dropped fault block bounded by two or more normal faults, with some minor flexing along the axis. The normal faults are high angle and expressed as obsequent faultline scarps. Tuwaiq Mountain Limestone forms the greater part of the ridge. Synclines at each end of the graben expose rocks of the Hisyān Member of the upper Dhrumā Formation. There is no Hanifa remaining above the Tuwaiq Mountain.

Although direct evidence is lacking here, displacement of Tuwaiq Mountain Limestone from its normal position above is estimated to be from 200 to 300 m.

MAJMA'AH GRABEN

The northernmost, or Majma'ah graben, is not structurally as simple as the other down-dropped blocks but rather is a system of overlapping faults and en echelon grabens. From its southern end near Al Qaṣab (lat 25°18' N., long 45°31' E.) the Majma'ah complex slices N. 20° W. through the Tuwayq front and continues along this trend approximately to the latitude of Al Ghāṭ (lat 26°02' N.). Northward, the structure swings gradually to N. 04° W. and dies out as a gentle monocline in Upper Cretaceous rocks at lat 26°36' N.

The possible extension of the Majma'ah graben southeastward under 'Urayq al Buldān is suggested by two outliers of Tuwaiq Mountain Limestone—one immediately west of Al Qaṣab and the other, Jabal al Fahdah, 12 km south-southeast of Al Qaṣab. These outliers, remnants of down-faulted blocks, occur in line with the projection of Majma'ah graben and lie along the northwestern projection of Barraḥ graben. Thus, the length of the Barraḥ and Majma'ah grabens may be greatly increased beyond the visible parts of their remnant ridges and, in fact, may represent parts of a single system now interrupted by Quaternary sand.

At the point where the Majma'ah graben intersects the Tuwayq Mountains, the graben changes from a prominent obsequent faultline ridge to a long, straight slot about 1 km wide walled in by opposing faces of Tuwaiq Mountain Limestone. Relief along most of this trough is 50 to 60 m, lessening toward the north. East of Al Ghāṭ the trough is a low sag containing a discontinuous ridge of hills formed of Middle and Upper Cretaceous rocks.

Along the southern part of the graben, Tuwaiq Mountain Limestone is faulted down against Dhurma, and Hanifa is down dropped against Tuwaiq Mountain Limestone. At the northern end, a group of Cretaceous hills, Jabal Ḥaṭṭābah, stands above the dissected upland surface of Tuwaiq Mountain Limestone. Movement is calculated to be 150 to 200 m at the southern end of the graben, progressively diminishing to 0 m in the extreme north.

On the evidence available, the age of faulting can be placed only as post-Late Cretaceous.

In summary, there is in central Arabia a complex of six grabens and two associated troughs that form a giant arc at least 500 km long and concave toward the northeast. It appears that faulting began in Upper Cretaceous time and continued at least through Paleocene and probably on into middle Eocene. The graben system probably marks a hinge line between a relatively stable land mass to the southwest and a periodically subsiding shelf to the northeast.

KHAWR UMM WU'AL GRABEN

Khawr Umm Wu'al, a narrow, linear trough, has been traced southeast from Umm Wu'al (lat 31°47' N., long 38°54' E.) to the northern edge of the Al Harrah lava field, a distance of some 135 km. The structure, 5 to 8 km wide, changes along its length from a simple syncline to a combined syncline and graben. Topographic relief on the walls of the trough does not exceed 100 m.

The margins of the khawr, in addition to being the sites of major faults, are also the loci of basalt dikes, plugs, and flows. Khawr Umm Wu'al graben apparently represents tensional adjustment to the growth of the Ha'il arch. Presumably the arch is a residual high between two areas of subsidence—the Sirbān-Turayf basin on the west and the Arabian Shelf on the east.

STRATIGRAPHIC SECTIONS

Detailed and generalized descriptions of stratigraphic sections cited in text follow. Significant stratigraphic details are shown graphically in figures 2 through 14 and plates 3 through 10 for most type and reference sections. Formations of constant, homogeneous and (or) incompletely known lithology not depicted in plates or stratigraphic sections are described in text. These include the Saq, Wajid, Hith, Wasia, and Khari Formations and the Tertiary and Quaternary surficial cover. Characteristic and diagnostic fossils are shown in the type and reference section plates, and complete fossil lists are included in the text. All section thicknesses are in the metric system. Formation names and corresponding place name spellings differ where the original type locality name was later revised and (or) altered through transliteration into the BGN/PCGN system. The original formation name spellings are perpetuated to avoid confusion in geologic nomenclature.

TABUK FORMATION SECTIONS

SECTION 1.—Tabuk and vicinity

[Tabuk type section description composed from several increments within an 64 km radius of Tabuk, measured and described in 1961 by R. A. Brankamp, C. W. Brown, S. J. Roach, and A. E. Clements]

Sandstone of Aruma Formation (Upper Cretaceous). Unconformity.

Tabuk Formation (top truncated):

	Thickness (meters)
7. Tawil Sandstone Member (177.0 m thick):	
Sandstone, light-brown and red, crossbedded, medium- to coarse-grained; fine-grained ferruginous matrix common and pebble beds abundant, locally hematitic and pisolitic.	56.0
Sandstone, light-brown, strongly crossbedded, medium- to coarse-grained, moderately cemented; occasional purple and light-gray shaly partings, locally contains a few quartz pebbles, considerable fine-pebble conglomerate in upper part.	30.5

SECTION 1.—Tabuk and vicinity—Continued

Tabuk Formation (top truncated)—Continued

7. Tawil Sandstone Member (177.0 m thick)—Continued

	Thickness (meters)
Sandstone, buff, crossbedded, moderately cemented, medium-grained; thin partings and layers of white to light-gray platy siltstone and fine-grained well-cemented sandstone. Local zones are finely nodular and ferruginous.	25.0
Sandstone, yellowish-brown, medium- to coarse-grained, in part crossbedded; scattered quartz pebbles, occasional layers of soft purple to greenish-brown sandstone, local partings of sandstone with ferruginous matrix.	9.5
Sandstone, yellowish-brown to brown, strongly crossbedded, moderately cemented, medium-grained; abundant black ironstone partings and ferruginous staining. A weak sandstone bench at top.	5.0
Sandstone, reddish-brown, well-cemented, crossbedded; in part with ferruginous matrix; surface weathers black with local ironstone concretions.	20.0
Sandstone, black- to brown-weathering, strongly ferruginous, fine- to coarse-grained; subordinate quartz conglomerate with ferruginous matrix. Forms thick ledge with prominent bench at top.	5.0
Sandstone, brown to golden-brown and coarse-grained, ferruginous; many conglomeratic layers. Weathers black in patches.	10.0
Sandstone, yellowish-brown, moderately cemented, crossbedded, coarse-grained; scattered quartz pebbles.	16.0
6. Sandstone (286.4 m thick):	
Sandstone, buff to yellow-brown, medium- to coarse-grained, massive-bedded, irregularly weathering.	8.7
Sandstone, white to light-gray, fine-grained, slabby-weathering.	2.0
Sandstone, pink-gray to buff, irregular patches of purple, well-cemented; common ironstone concretions in upper part. Prominent bench at top.	2.5
Sandstone, white, gray, and dark-brown; many irregular ironstone partings, commonly nodular. Forms prominent ledge.	19.2
Sandstone, buff, gray, and purple, fine-grained, well-bedded; abundant tubular casts.	14.4
Sandstone, gray to buff and purple, fine-grained; abundant tubular casts.	20.8
Sandstone, purple-gray to buff, semifrangible, massive; abundant vertical tubular casts, large sacklike masses of buff well-cemented sandstone with concentric structure.	4.5
Sandstone, gray and purple, well-bedded, fine-grained; many irregular, concentrically banded masses of fine-grained sandstone near middle.	3.5

SECTION 1.—*Tabuk and vicinity*—Continued

Tabuk Formation (top truncated)—Continued

6. Sandstone (286.4 m thick)—Continued

	Thickness (meters)
Sandstone, pink to gray, fine-grained, well-cemented; many brown ferruginous partings with irregular organic(?) markings (tracks?).....	8.0
Sandstone, purple and gray, medium-bedded, fine-grained; abundant tubular casts.....	6.4
Concealed.....	12.8
Sandstone, gray, buff, and brown, well-bedded, silty, in part micaceous, fine-grained; forms cliff capped by 1.0-m-thick ledge of resistant sandstone.....	10.8
Sandstone, buff to pale-green, in part limonite-stained, friable, silty, fine-grained.....	1.5
Sandstone, brown-weathering, ledges of gray, in part micaceous, silty, fine-grained; ferruginous layers and splotches, rare worm(?) trails.....	13.0
Sandstone, tan to white and purple-mottled, moderately cemented, fine-grained; numerous short straight tubular root(?) casts. A brown-weathering, somewhat harder sandstone forms weak ledge at top.....	7.1
Sandstone and siltstone, purple to olive-green, shaly, fine-grained; forms slope. <i>Cruziana</i> tracks in scree near middle.....	32.6
Sandstone and siltstone; alternating thin layers of purple, dark-red, greenish-gray, light-gray fine-grained micaceous silty sandstone and finely sandy siltstone.....	15.0
Sandstone and shale; olive-green micaceous silty sandstone and sandy shale.....	5.2
Sandstone, purplish-gray, thinly bedded, fine-grained, micaceous.....	0.2
Concealed.....	2.1
Shale and siltstone; medium-gray micaceous silty shale and siltstone; thin beds and irregular lenses purplish-brown sandstone. Upper 1.5 m thinly crossbedded and in part ripple marked.....	11.7
Sandstone, white to gray and dark-red, fine-grained, silty, micaceous; rarely ripple marked and crossbedded.....	23.1
Sandstone, gray, fine-grained, silty, micaceous; platy to finely laminated beds 0.1 to 0.2 m thick in part separated by equally thin beds of olive-green micaceous silty shale.....	20.0
Sandstone, gray and red-brown, thinly bedded, micaceous, silty, fine-grained; weak bench at top.....	5.1
Covered; fragments of dark-green scree suggest this interval largely shale with minor sandstone.....	5.1
Sandstone, olive-green to brown, ripple-marked, micaceous, well-laminated, very fine grained; commonly iron stained.....	31.1

SECTION 1.—*Tabuk and vicinity*—Continued

Tabuk Formation (top truncated)—Continued

5. Shale and siltstone (290.5 m thick):

	Thickness (meters)
Siltstone and sandstone; complexly alternating layers of olive-green to gray micaceous siltstone and buff to gray-brown, largely micaceous, well-bedded fine-grained sandstone.....	34.4
Siltstone and shale; gray to brown to olive-green, slightly micaceous siltstone and silty shale; few thin layers of brown ferruginous fine-grained sandstone, thin wavy bedding common.....	9.1
Sandstone, purplish-brown to brown, ferruginous, slightly micaceous, fine-grained. Shale and siltstone; greenish-gray to olive-gray, irregularly bedded, in part micaceous, silty shale and siltstone; thin layers of pinkish-brown to brownish-gray fine-grained, slightly micaceous sandstone. Thin (0.5 m) sandstone bed at top forms prominent bench.....	1.0
Siltstone, greenish-gray, micaceous; subordinate shale and very fine grained micaceous sandstone. Thin sandstone bed at top forms prominent bench.....	35.6
Sandstone, shale, and siltstone; complexly interbedded layers of brown fine-grained sandstone, olive-green micaceous silty shale, and siltstone. Forms prominent bench.....	15.8
Sandstone, brown, speckled, slightly cross-bedded, micaceous, fine-grained.....	4.4
Shale, gray to olive-green and purple, strongly micaceous, silty; few thin sandstone interbeds.....	0.3
Shale, siltstone, and sandstone; olive-gray to light-purple, strongly micaceous and silty shale and siltstone; thin ripple-marked layers of micaceous fine-grained sandstone.....	62.5
Siltstone and sandstone; complexly mixed and thinly interbedded olive-green to gray micaceous siltstone and fine-grained sandstone; lower part includes some light-gray and purple-weathering shale. Entire interval poorly exposed and may be slumped.....	14.8
Sandstone, light-gray to dark-brown, thinly bedded, in part ripple-marked, fine-grained, ferruginous, micaceous, and silty; subordinate interbedded shale exposed as a series of weak ledges.....	17.5
Shale and siltstone; purple-gray and some greenish-gray, limonite-stained, strongly micaceous silty shale and siltstone; thin, platy layers of buff to gray micaceous fine-grained sandstone with yellow staining in upper part.....	4.0
Shale, brown to gray, strongly flaky, silty and micaceous; poorly preserved graptolites at several levels.....	34.8
Sandstone, brown, crossbedded, moderately cemented, fine-grained.....	18.3
	0.5

SECTION 1.—*Tabuk and vicinity*—Continued

Tabuk Formation (top truncated)—Continued

	Thickness (meters)
5. Shale and siltstone (290.5 m thick)—Continued	
Shale, purple and gray, silty, micaceous.....	0.6
Sandstone, brown, crossbedded, moderately cemented, fine-grained.....	0.3
Shale, gray to brown and purple, in part silty and micaceous; occasional irregular platy beds of tan fine-grained sandstone.	24.5
Sandstone and shale; light-brown to buff and yellow thin-bedded fine-grained sandstone; alternating layers of purple and gray silty shale. Weak sandstone bench at top.....	8.7
Sandstone, gray to brown, thin-bedded, fine-grained; some purple and gray micaceous silty shale.....	3.4
4. Sandstone (104.9 m thick):	
Sandstone, tan to brown, commonly black-weathering, fine-grained, micaceous, in part silty; partings of olive-green shale common.....	72.1
Sandstone, tan to brown, ripple-marked, fine-grained, micaceous, silty, thin-bedded; exposed as series of thin sandstone ledges followed by poorly exposed slopes of soft sandstone.....	32.8
3. Poorly exposed (70.7 m thick):	
Poorly exposed; few coherent sandstone beds form thin resistant ledges separated by scree-covered slopes; digging indicates covered intervals mostly brown and purple micaceous silty shale with occasional thin beds of platy siltstone.....	63.8
Shale, dull-gray to brown, white-weathering, silty; <i>Diplograptus</i> 4 m above base of unit. Interval considerably disturbed; probably slumped.....	5.2
Concealed.....	1.7
2. Sandstone (129.8 m thick):	
Sandstone, brown, black-weathering, medium- to coarse-grained, moderately cemented; some quartz pebbles. Interval not measured; thickness estimated.....	35.0
Sandstone, pink, fine- to medium-grained, moderately cemented, crossbedded; conglomeratic layers with quartz, pink limestone, and shale pebbles.....	2.1
Shale and sandstone; red to purple and white, thinly interbedded silty shale and light-gray fine-grained, in part calcareous, micaceous sandstone; poorly exposed.....	20.8
Siltstone, pearl-gray, shaly, in part micaceous.....	2.0
Sandstone, pink and tan, moderately cemented, in part crossbedded.....	2.9
Sandstone, off-white to gray, brown-weathering; massively bedded in lower part and strongly crossbedded in upper part. Forms prominent ledge.....	29.0

SECTION 1.—*Tabuk and vicinity*—Continued

Tabuk Formation (top truncated)—Continued

	Thickness (meters)
2. Sandstone (129.8 m thick)—Continued	
Sandstone, gray to brown, moderately cross-bedded, commonly ripple-marked; thin bedded with alternating hard and soft layers.....	31.0
Shale, olive-green, in part micaceous and silty; increasing interbedded platy sandstone toward top.....	7.0
1. Hanadir member (12.2 m):	
Shale, purple and gray, thin-bedded, platy, in part calcareous; several ferruginous limestone layers. Abundant <i>Didymograptus protobifidus</i>	12.2
Total thickness of Tabuk Formation.....	1071.5
Saq Sandstone.....	

SECTION 2.—*Taymad' to Al Huj*

[Generalized section of Tabuk Formation from Taymad' to Al Huj, N. M. Layan, Jr. and D. O. Reese, 1969]

	Thickness (meters)
Siltstone and limestone of Jaul Formation (Lower Devonian).	
Tabuk Formation:	
5. Tawil Sandstone Member: Sandstone, buff to red-brown, weathering black and dark-brown, medium- to coarse-grained, commonly gravel-bearing; conspicuous crossbedding or graded bedding throughout. Layers of ironstone at base and several higher levels. Upper beds usually form cliffs or hills.....	200.0
4. Upper pre-Tawil sandstone: Sandstone, gray to brown, fine- to medium-grained, in part cross-bedded; vertical tubular structures (<i>Scolithus</i>) common. Much of interval is poorly exposed and thickness of covered sections computed.....	196.0
3. Upper siltstone: Siltstone, dominantly gray, gray-green and buff; <i>Scolithus</i> common. Siltstone is complexly interbedded with subordinate sandstone and shale. Sandstone is variously red, brown, gray, or tan, fine grained, thin bedded, ferruginous, silty, micaceous, and flaggy weathering, with some ripple marks. The shale is olive green, gray, brown, and micaceous.....	346.0
2. Lower sandstone: Sandstone, gray, brown, red-brown, fine- to medium-grained, thin-bedded; <i>Scolithus</i> common, occasional beds of gray and greenish-gray shale and siltstone.....	222.0
1. Lower shale (Hanadir member): Shale, olive-gray to reddish-brown, micaceous and silty; thin interbeds of reddish-brown, fine-grained, silty and micaceous sandstone common. <i>Didymograptus protobifidus</i> common.....	60.0
Total thickness of Tabuk Formation.....	1024.0
Saq Sandstone.....	

SECTION 3.—Qusaibā'

[Generalized section of Tabuk Formation near lot of Qusaibā' measured by A. F. Pocock and R. P. Kopp, 1949, and N. M. Layne, Jr., and H. W. Blodgett, 1950]

Limestone of Khuff Formation (Upper Permian).

Unconformity.

Tabuk Formation:	Thickness (meters)
6. Upper sandstone: Sandstone, brown, fine- to medium-grained, thin-bedded; commonly ripple marked. A yellow-gray gypsiferous soft shale bed with stringers of gray friable fine-grained crossbedded sandstone and red and yellow friable crossbedded sandstone caps the unit. May include beds equivalent to Tawil Sandstone Member.....	32.0
5. Upper shale (Qusaibā' member): Shale, varicolored, but mostly gray-green, laminated; more gypsiferous and with thin beds of red, hematitic siltstone in upper part; lower part is graptolitic. Poorly sorted gray medium-grained thin-bedded sandstone and highly weathered calcareous beds at top of unit.....	57.4
4. Middle sandstone: Sandstone, light-red and pale-yellow, medium-grained, distinctively crossbedded, mostly well-sorted; nodular weathering; few very thin dark sericitic shale and silty beds near middle. Duricrust locally covers exposures.....	241.5
3. Middle shale (Ita'an member): Shale, gray to greenish-gray, sericitic; thin interbeds of silty, silty sandstone, and fine-grained sandstone. Several red-brown to gray-brown fine-grained well-sorted sandstone beds are near top, and greenish-gray to yellow-gray sericitic shale caps the member. Graptolites at base.....	67.0
2. Lower sandstone: Sandstone, light-colored (yellow, white, pink), medium- to fine-grained, crossbedded; occasional sericitic beds and some nodular weathering. Sericitic siltstone in lower part.....	220.2
1. Lower shale (Ifanadir member): Shale, greenish-gray to yellow, in part gypsiferous and sericitic; interbedded brown and red-brown fine-grained sericitic sandstone and some well-laminated siltstone toward the bottom. Graptolites in lower part.....	59.1
Total thickness of Tabuk Formation.....	677.2

Saq Sandstone.

SECTION 4.—Jildiyah to Ash Shu'aybah

[Generalized section of Tabuk Formation from Jildiyah to Ash Shu'aybah measured by A. F. Pocock and R. P. Kopp, 1949]

Limestone of Jauf Formation (Lower Devonian).

Tabuk Formation:	Thickness (meters)
4. Upper sandstone: Sandstone, poorly exposed, light-brown and gray to white, fine- to medium-grained, mostly crossbedded; greenish-gray thin-bedded sericitic shale near top. May be all or in part equivalent to Tawil Sandstone Member.....	125.2

SECTION 4.—Jildiyah to Ash Shu'aybah—Continued

Tabuk Formation—Continued

Tabuk Formation—Continued	Thickness (meters)
3. Upper shale (Qusaibā' member): Shale, in part unexposed, tan, gray, greenish-gray, commonly sericitic and gypsiferous; interbedded with gray fine-grained thin-bedded sandstone, a few siltstone stringers, and very thin, rare and impure limestone lenses.....	125.9
2. Middle and lower sandstone: Sandstone, brown and yellow-white, medium- to coarse-grained in upper part, red to purple and fine-grained in lower part; occasionally crossbedded and nodular weathering. Thin sericitic siltstone layers in middle and lower part common.....	395.2
1. Lower shale (Ifanadir member): Shale, in part poorly exposed, purple to olive-green, brown, red, silty, sericitic; graptolitic in basal beds. Several thin brown fine-grained, in part gypsiferous, sandstone beds.....	68.5
Total thickness of Tabuk Formation.....	714.8

Saq Sandstone.

JAUF FORMATION SECTIONS

SECTION 5.—Jauf and vicinity

[Jauf Formation type section measured and described by A. F. Pocock, S. Beven, and H. W. Schneider in 1950 in Al Jawf and vicinity]

Sandstone of Wasia (Sakaka) Formation (Middle Cretaceous). Unconformity. Jauf Formation:	Thickness (meters)
4. Upper clastics (transition beds, 27.1 m thick): Sandstone, reddish-tan, very fine grained, poorly bedded; zones of thinly laminated sericitic sandstone.....	2.0
Siltstone and silty shale; brown siltstone and gray-green to gray silty shale; occasional laminations of marl and a few thin layers of platy silty limestone in middle part.....	10.7
Dolomite, reddish-tan, dense, very thin bedded, microcrystalline to saccharoidal.....	0.1
Sandstone and siltstone, thin, alternating beds.....	5.0
Sandstone, fine-grained, micaceous; becomes siltstone at base.....	2.1
Limestone, gray-tan, thin-bedded, platy, impure.....	0.2
Sandstone, light-gray to tan, fine-grained, well-sorted, subangular, friable, commonly crossbedded; includes some gray and tan sericitic and silty shale. Interval shows rapid lateral lithologic change.....	7.0
3. Upper limestone (Hammamiat member, 106.3 m thick): Limestone, gray-tan, detrital; poorly exposed on beveled dip slope. Entire interval thin bedded. Some greenish-yellow fine-grained limonite-stained, slightly silty limestone.....	7.6
Limestone, gray, medium-bedded, finely porous, in part impure; weathers to steel gray.	1.9
Siltstone, mustard-yellow, poorly exposed.....	1.5
Shale, gray, silty; occasional thin beds of reddish-tan fine-grained sandstone.....	5.5

SECTION 5.—Jauf and vicinity—Continued

Jauf Formation—Continued

3. Upper limestone (Hammamiyat member, 106.3 m thick)—Continued

	Thickness (meters)
Sandstone, reddish-tan, fine-grained, semi-friable, sericitic, highly lenticular.....	2.3
Shale, gray to grayish-green, silty; subordinate gray fine-grained sandstone and siltstone.....	10.7
Limestone, gray to tan, thinly laminated, platy, impure; grades upward to siltstone..	8.7
Silt, white to light-greenish-yellow; poorly exposed.....	6.3
Dolomite, grayish-tan, saccharoidal: thin interbeds of slate-gray lithographic limestone and tan mottled detrital limestone.....	0.7
Limestone, greenish-tan, dense, silty.....	0.8
Siltstone and shale; interval includes equal amounts of tan thin-bedded sericitic siltstone and grayish-green silty shale.....	7.0
Limestone and siltstone; complexly interbedded tan marly limestone and gray sericitic siltstone; occasional thin beds of cream-colored detrital limestone and fine-grained sericitic sandstone.....	7.0
Limestone, yellow to gray-tan, dense, very finely crystalline to microcrystalline; subordinate silty limestone.....	1.7
Shale, light-greenish-gray, thinly laminated, marly; thin beds of gray-tan silty, finely detrital limestone near top.....	1.5
Shale, gray-green, silty; rare laminations of reddish-tan, slightly platy siltstone. Forms laterally persistent shale zone.....	11.1
Siltstone, cream to gray, marly.....	1.7
Limestone and siltstone, tan, thin-bedded, dense limestone; an approximately equal amount of yellow-tan thin-bedded siltstone. Poorly exposed.....	5.9
Limestone, tan (gray-mottled), dense, thin-bedded, very finely crystalline to microcrystalline; in part slightly silty.....	6.5
Siltstone, cream-colored to gray; capped by 0.5 m of tan and white-speckled fine-grained sandstone.....	10.5
Limestone, yellow to gray-tan, dense, thin-bedded, in part impure; lower part poorly exposed.....	4.7
Limestone, brownish-tan, thin- to medium-bedded, dense, finely crystalline; thin bed of mustard-tan, slightly silty limestone at base.....	2.7
2. Middle shale (Subbat member, 113.4 m thick):	
Siltstone, creamish-tan, thinly laminated, sericitic.....	0.2
Sandstone, brown, fine-grained, friable; grades upward into brown, thinly laminated, platy, impure limestone.....	2.2
Sandstone, gray-brown, thin-bedded, friable, fine-grained.....	5.2
Shale, gray-green, silty; subordinate maroon and gray-brown siltstone, occasional partings of fine-grained sandstone.....	17.7

SECTION 5.—Jauf and vicinity—Continued

Jauf Formation—Continued

2. Middle shale (Subbat member, 113.4 m thick)—Continued.

	Thickness (meters)
Sandstone, light-brown, fine-grained, well-sorted, friable, crossbedded to massive....	3.8
Shale, gray, silty; common maroon hematitic partings. Thin interbeds of brown impure limestone and fine-grained sandstone.....	7.1
Shale, sandstone and siltstone; alternating laminations of gray-green, slightly silty shale and fine-grained flaky micaceous sandstone and siltstone; interval capped by 1.0-m-thick bed of tan, moderately hard, impure limestone.....	3.7
Sandstone, tan, thin-bedded, fine-grained, friable.....	0.5
Shale, grayish-green, slightly silty; common hematitic partings.....	3.5
Sandstone and shale; gray-green silty shale overlain by white soft fine-grained sandstone.....	2.1
Shale and siltstone; gray-green silty shale and siltstone; interval capped by a 10-m-thick bed of gray-brown, very fine-grained, platy sandstone.....	17.6
Shale, gray and maroon, very silty.....	21.0
Sandstone, white, fine-grained, well-rounded, well-sorted, friable.....	0.3
Shale, bands of maroon and light-gray, finely silty; weathers to nodules. Lower 3.5 m poorly exposed.....	28.5
1. Lower limestone and shale (Qasr member, 52.4 m thick):	
Limestone, grayish-tan, dense, thin-bedded, fossiliferous; abundant fossil casts give weathered surface pisolitic appearance; upper 3.4 m poorly exposed in dip slopes... Covered; probably yellow, marly siltstone...	7.2
Limestone and siltstone; yellow-tan thin-bedded impure limestone; poorly exposed interbedded soft siltstone.....	4.0
Limestone, gray-tan, thin-bedded; poorly exposed subordinate yellow-tan platy silty limestone.....	2.5
Limestone, gray-tan, dense, thin-bedded; commonly thin-bedded; abundant small casts give weathered surface pebble-grained appearance. Small reef buildups common in this interval.....	2.0
Limestone, gray-tan, dense, thin-bedded; abundant weathered gastropod and brachiopod casts in upper part.....	2.1
Siltstone, green-tan, thin-bedded, platy, marly; grades upward into tan, very fine fine crystalline marl.....	1.0
Shale, gray and some maroon, silty; grading upward to tan silt at top.....	2.1
Shale and siltstone; blue-green shale grading upward to brown thin-bedded marly siltstone.....	6.0
Sandstone, pinkish-tan (black-mottled), very fine-grained, well-cemented; grades laterally to calcareous siltstone.....	5.2
	0.3

SECTION 5.—Jauf and vicinity—Continued

Jauf Formation—Continued

1. Lower limestone and shale (Qasr member, 52.4 m thick)—Continued	Thickness (meters)
Shale, gray-green; capped by a thin bed of tan marl.....	5.3
Siltstone, light-tan, thin-bedded, slightly marly.....	1.2
Shale, gray and maroon, silty.....	4.0
Sandstone, brown (black-mottled), fine-grained, moderately hard, well-sorted, block-weathering.....	0.3
Shale, tan to gray; subordinate thin beds of tan platy impure limestone. Shale becomes more silty toward top. Capped by thin bed of pink-weathering platy impure limestone.....	7.2
Shale, gray and maroon; capped by 4-cm-thick bed of platy impure limestone.....	2.0

Total thickness of Jauf Formation..... 299.2

Tabuk Formation (Tawil Sandstone Member).

SECTION 6.—Al Haliwa

(Generalized section of Jauf Formation at Al Haliwa after N. M. Layne, Jr., and D. O. Reese, 1969)

Sandstone of Wasia (Sakaka) Formation (Middle Cretaceous).

Unconformity.

Jauf Formation:

3. Upper limestone (Hammamiyat member, 61.5 m thick):	Thickness (meters)
Shale, dominant, olive and purple, often gypsiferous; subordinate interbedded gray and tan-brown medium-grained cross-bedded friable sandstone. Single 5.0-m thick bed of tan, finely crystalline, partially dolomitized, calcarenitic limestone forms ledge at top of interval.....	41.7
Limestone, mostly calcarenitic, gray and reddish-brown, in part impure, partially dolomitized; subordinate thin interbeds of brown medium-grained, slightly micaceous, somewhat calcareous sandstone.....	19.8
2. Middle shale (Subbat member):	
Shale, green and olive, reddish-brown and maroon, commonly gypsiferous; thin interbeds of gray to brown medium-grained friable, often silty sandstone. A 1.7-m-thick bed of off-white to cream impure blocky-weathering limestone near base.....	106.7
1. Lower limestone and shale (Qasr member):	
Shale, yellow, gray, and purple, chippy-weathering, in part silty; banded gypsum common in lower part. Several thin beds of tan impure, in part fossiliferous limestone and gray dolomite. Single thin bed of brown to black sandy gypsiferous ironstone at base.....	38.7

Total thickness of Jauf Formation..... 206.9

Tabuk Formation (Tawil Sandstone Member).

KHUFF FORMATION SECTIONS

SECTION 7.—Ar Rayn

(Khuff Formation reference section measured and described in the vicinity of Ar Rayn by R. A. Bramkamp, E. L. Berg, R. L. Myers, and W. T. Short in 1946)

Shale (Upper Permian) of Sudair Shale.

Khuff Formation:

4. Aphanitic and calcarenitic limestone (28.2 m thick):	Thickness (meters)
Dolomite, tan to brownish-red, blocky-weathering, medium-grained, crystalline; locally grades to strongly recrystallized, fine-grained calcarenite. Forms prominent bench.....	2.0
Limestone, yellow, limonite-stained, marly, fine-grained; a few bedding planes in upper part with abundant small clams on weathered surface.....	9.2
Limestone, medium-grained crystalline; many limonite stains and limestone pebbles and fragments locally common.....	0.4
Marl, yellow, limonite-stained, moderately indurated; in part with questionable molds of small clams.....	1.7
Limestone, white, finely crystalline; weathers to heavy ledges with ellipsoidal boulders. Basal 0.5 m sandy.....	12.2
Covered.....	1.0
Limestone, golden-brown to gray, chippy, to blocky-weathering, tight, finely crystalline; brachiopods locally common.....	1.7
3. Aphanitic limestone (71.1 m thick):	
Limestone, tan to light-gray, rubbly-weathering, compact, fine-grained; upper part massive and forms moderate bench.....	4.1
Poorly exposed; probably marl or marly limestone.....	3.5
Dolomite, light-gray to tan, compact, finely crystalline.....	1.0
Limestone, brown, porous-weathering, fine-grained; forms weak bench.....	0.1
Covered; much gypsum in weathered zone.....	0.3
Limestone, gray-white, rubbly-weathering, fine-grained.....	0.1
Covered; probably shale; much gypsum in weathered zone.....	0.8
Limestone, white, fine-grained.....	0.2
Limestone and shale; complexly interbedded white to brown rubbly-weathering fine-grained limestone and olive-green shale; shale intervals poorly exposed with much gypsum in weathered zone.....	2.7
Dolomite, off-white, marly, finely crystalline.....	2.8
Limestone, light-gray to brown, rubbly- to slabby-weathering, compact, fine-grained; many large limestone pebbles and cobbles (intraformational conglomerate) and a few small subpherical siliceous bodies in upper 1.0 m.....	6.0
Dolomite, gray-tan, finely crystalline; many subpherical siliceous bodies, in part solid, and in part miniature geodes.....	0.3
Limestone, light-gray to brown, rubbly-weathering, poorly exposed, compact, fine-grained; thin interbeds off-white soft marl.....	6.1

SECTION 7.—*Ar Rayn*—Continued

Khuff Formation—Continued

3. Aphanitic limestone (71.1 m thick)—Continued	Thickness (meters)
Limestone, light-gray to brown, rubbly-weathering, compact, very finely crystalline, partially dolomitized.....	1.2
Poorly exposed; probably shale.....	6.0
Limestone and dolomite, tan, poorly exposed, rubbly-weathering, fine-grained limestone; some marly-weathering, finely crystalline dolomite.....	2.7
Limestone, off-white to gray, rubbly-weathering, fine-grained; several thin oolitic layers. Interval capped by thin oolite-coquina beds.....	1.7
Limestone, off-white to gray, soft, rubbly-weathering, fine-grained; commonly marly.	24.0
Shale, gray-green, partly covered.....	5.1
Limestone, light-tan to light-gray, marly-weathering, compact, partially dolomitized, finely crystalline.....	0.8
Shale, olive-green, poorly exposed.....	1.6
2. Dolomite and limestone (33.7 m thick):	
Coquina, tan to gray, porous, partially recrystallized; abundant indeterminate small fossils.....	0.2
Dolomite, tan, soft, marly, finely crystalline.....	1.6
Limestone, light-tan to gray, compact, fine-grained.....	0.3
Dolomite, tan, light-gray-weathering, soft, marly, finely crystalline; rare fragments of silicified wood on surface, none definitely in place.....	6.0
Limestone, gray, flaggy-weathering, compact, fine-grained.....	1.0
Limestone, tan, soft, marly, partially dolomitized, fine-grained; a few thin slabby gray-brown beds. Indeterminate nautiloid at base.....	1.7
Calcarenite, gray-brown, thin-bedded, strongly cemented, very fine to fine-grained, oolite(?); forms moderate bench.....	0.8
Shale, olive-green, poorly exposed; many thin beds of platy gray-brown, finely crystalline limestone.....	3.5
Calcarenitic limestone, brown to tan, partially recrystallized, shelly.....	1.5
Calcarenite, tan, strongly cemented, partially recrystallized, very fine to fine-grained oolite(?); forms strong bench.....	1.3
Dolomite, light-gray, rubbly, thin-bedded, compact, finely crystalline.....	6.7
Limestone, tan to brown and gray, compact, fine-grained; brachiopodal, shelly and oolitic(?) in lower part.....	5.9
Limestone, off-white, poorly exposed, marly-weathering; a 0.1-m-thick bed of gray, strongly cemented, Foraminifera-oolite calcarenite 0.7 m below top.....	3.2
1. Dolomite and shale (38.4 m thick):	
Dolomite, light-tan, compact, finely crystalline; forms strong bench.....	0.4
Covered.....	2.3

SECTION 7.—*Ar Rayn*—Continued

Khuff Formation—Continued

1. Dolomite and shale (38.4 m thick)—Continued	Thickness (meters)
Dolomite, off-white to light-gray, rubbly-weathering, thin-bedded, compact, finely crystalline; many veins of clear prismatic calcite in lower part.....	8.4
Shale, olive-green, gypsiferous.....	5.0
Dolomite, gray, tight, finely crystalline; rare chert near top.....	1.3
Limestone and dolomite; tan to gray thick-bedded compact fine-grained limestone complexly interbedded with gray-brown, finely crystalline dolomite; several resistant beds with rare indeterminate small organic remains.....	8.8
Shale, poorly exposed, tan, marly, gypsiferous.....	10.7
Conglomerate, pink and white, moderately cemented, poorly sorted, angular granitic sand and fine conglomerate.....	1.5

Total thickness of Khuff Formation..... 171.4

Nonconformity.

Granite of basement complex.

SECTION 8.—*Wadi Maghrib*

[Generalized section of Khuff Formation in vicinity of Wadi Maghrib (type section locality) measured by D. A. Helm and A. F. Focock, 1946]

Shale (Upper Permian) of Sudair Shale

Khuff Formation:	Thickness (meters)
3. Upper limestone (Khartam member): Limestone, tan, commonly sandy; grades upward into gray to tan platy limestone with common oolitic texture. Substantial proportion of interval believed to contain marl although softer rock types are not cleanly exposed.....	25.0
2. Middle shale (Midhnab member): Shale, gray-blue to tan, plastic, often delicately banded, gypsiferous; subordinate marly limestone and bedded gypsum.....	70.0
1. Lower limestone (Khuff member): Lower half of member gray platy-weathering crystalline limestone; soft marly limestone at base. Grades upward into tan crystalline limestone overlain by gray hard limestone with individual beds usually 3 to 6 inches in thickness. Top of this interval forms a rough, blocky upland surface that becomes red, pitted, and scoriaceous on weathering. Upper half of unit contains increasing amounts of soft marly limestone and tan to mustard-colored shale, exposures largely obscured by blocky talus. Uppermost bed is 0.5 m of tight gray limestone forming persistent dip slope.....	140.0
Total thickness of Khuff Formation.....	235.0
Uneconformity.	
Saq Sandstone.	

SECTION 9.—Near lat 26°30' N.

[Generalized section of Khuff Formation north of type locality near lat 26°30' N. measured by A. F. Pockock and R. P. Kopp, 1949]

Sand and shale (Upper Permian) of Sudair Shale. Khuff Formation:	Thickness (meters)
3. Upper limestone (Khartam member): Limestone, light-brown to gray, poorly exposed; in part oolitic and fossiliferous. Basal part is yellow to off-white soft porous, rarely oolitic, impure limestone thinly interbedded with platy crystalline limestone.	81.5
2. Middle shale (Midhbab member): Upper part is poorly exposed yellow gypsiferous shale and siltstone complexly interbedded with fine- to medium-grained friable sandstone with fine, grained oolites. Light-gray friable, highly gypsiferous shale and gray subrounded, moderately hard, thin-bedded fine-grained sandstone occur at the base. Lower part is covered by duricrust, but probably consists of gray to green, finely laminated shale with thinly interbedded gypsum and marl.	70.2
1. Lower limestone (Khuff member): Limestone, gray to reddish-gray, hard, microcrystalline; gray to cream medium-grained, moderately sorted subrounded soft sandstone occurs near the bottom; base of interval unexposed.	140.5
Total thickness of Khuff Formation.	292.2
Unconformity.	
Tabuk Formation.	

SECTION 10.—Al Mulaib

[Generalized section of Khuff Formation near Al Mulaib (lat 27°30' N.) measured by R. D. Gierhart and L. F. Ramirez, 1949]

Shale (Upper Permian) of Sudair Shale. Khuff Formation:	Thickness (meters)
2. Upper dolomite: Dolomite, dominant, gray to brown and red, thin-bedded, commonly platy-weathering, occasionally shelly, in part gypsiferous; subordinate interbeds of light-colored soft marly limestone, red and green gypsiferous shale, red to brown siltstone, and off-white to brown friable fine-grained sandstone.	103.0
1. Lower limestone: Limestone, off-white to gray and brown, soft, marly, rubbly-weathering; some interbedded red and green shale. Single bed of dark-gray fine-grained platy-weathering sandstone exposed near base. Nearly one-half of interval covered and poorly exposed.	121.0
Total thickness of Khuff Formation.	224.0
Basement complex.	

SECTION 11.—Al 'Arid escarpment

[Generalized section of Khuff Formation exposed in Al 'Arid escarpment at Khatham Sudair and Jabal 'Umm Ghirán. Upper and middle Khuff measured by R. B. Henry and R. A. Bramkamp, 1950; lower Khuff by R. D. Gierhart and L. D. Owens, 1949]

Shale (Upper Permian) of Sudair Shale. Khuff Formation:	Thickness (meters)
3. Upper Khuff: Sandstone, dominant, white, massive, medium- to coarse-grained; subordinate red and green silty shale.	48.0

SECTION 11.—Al 'Arid escarpment—Continued

Khuff Formation—Continued	Thickness (meters)
2. Middle Khuff: Sandstone, white to partly pink and red, massive, fine- to medium-grained; middle part of interval is complexly interbedded dark-brick-red silty shale and white silty sandstone.	50.0
1. Lower Khuff: Sandstone, white, gray- and red-mottled, poorly exposed, in part crossbedded; some lenses of red and green shale and fossil wood.	56.0
Total thickness of Khuff Formation.	154.0
Wajid Sandstone.	

SUDAIR SHALE SECTION

SECTION 12.—Al 'Arid

[Sudair Shale type section composed from several measurements made by R. D. Gierhart and L. D. Owens in 1948 and R. D. Gierhart and R. A. Bramkamp in 1950 along the Al 'Arid escarpment at Khatham Ghudayr and Khatham Abb Hamadhah]

Sandstone of the Dhurma Formation (Middle Jurassic).

Unconformity.	Thickness (meters)
Sudair Shale:	
Shale, brick-red, platy, indurated; forms weak cliff.	2.4
Shale, alternating brick-red and gray.	22.6
Shale, poorly exposed, apparently brick-red as above.	3.4
Shale, gray, very sandy; forms weak cliff.	1.7
Shale, alternating brick-red and gray, sandy.	1.7
Shale, poorly exposed, probably brick-red as above.	34.0
Siltstone and limestone; complexly interbedded light-gray, strongly platy, slightly micaceous, calcareous siltstone and off-white argillaceous and silty limestone; forms moderate ledge.	0.6
Shale, dark-brick-red.	0.8
Siltstone, off-white to light-gray, platy, slightly micaceous, calcareous.	0.6
Shale, dark-brick-red.	1.6
Siltstone and shale; greenish-gray, thinly platy, slightly micaceous, calcareous siltstone and greenish-white silty shale.	1.5
Shale, dark-brick-red; thin layers of greenish-white calcareous shale 1.0 and 2.4 m below top.	8.6
Shale, greenish-white, calcareous.	0.3
Shale, dark-brick-red; a few 1- to 2-cm layers of greenish-white silty shale.	24.1
Shale, alternating greenish-white and dark-brick-red; several thin beds of silty friable sandstone.	3.5
Shale, brick-red.	1.1
Shale, alternating greenish-white and red.	0.3
Shale, brick-red, massive; silty and sandy near base.	
Several bands of green shale.	6.2
Shale and sandstone; thinly interlaminated greenish-white silty and sandy shale and pink to white fine-grained sandstone.	1.0
Total thickness of Sudair Shale.	116.0
Khuff Formation.	

JILH FORMATION SECTIONS

SECTION 13.—*Jilh al 'Ishar*

(*Jilh* Formation type section measured and described across the *Jilh al 'Ishar* escarpment by M. Steucke, E. L. Berg, R. L. Myers, and W. T. Short in 1943)

Sandstone of the Minjur Sandstone (Upper Triassic).

Upper *Jilh* Formation (184.0 m thick):

5. Sandstone, siltstone, and shale (66.2 m thick):

Limestone, yellow-brown, thinly bedded, slabby-weathering, fine-grained; alternating with yellow marly limestone. Rare marine fossils.

Shale, yellow; thin streaks of yellow platy limestone and soft marl. Forms distinctive marker bed.

Covered; probably shale.

Limestone, gray to dark-brown, sandy; top forms prominent dip slope.

Sandstone, friable, fine-grained; common thin stringers of siltstone.

Sandstone, gray, crossbedded, fine- to medium-grained, very friable.

Covered; probably silt and fine-grained sandstone.

Limestone, gray to tan, blocky-weathering, tight.

Covered; probably silt and shale.

Sandstone, fine-grained, in part calcareous.

Covered; probably silt and shale.

Limestone, golden-brown, thinly bedded, tight.

Sandstone, fine-grained; very thin interbeds of silt, shale, and golden-brown limestone.

Limestone, golden-brown, tight, slabby-weathering.

Shale, green; subordinate siltstone and some soft sandstone.

Sandstone, gray to brown, massive, crossbedded, medium-grained; occasional lenses of coarse-grained sandstone and gravel.

Siltstone, greenish-gray, soft, friable; some shale and sandstone. Forms face of escarpment.

Sandstone, light-brown, crossbedded, medium-grained.

Shale, green, commonly sandy.

Sandstone, thinly bedded, fine-grained, platy.

Shale, green, silty; common partings of purple and gray sandy shale.

4. Sandstone (117.8 m thick):

Sandstone, brownish-black, crossbedded, medium-grained; many black iron-stained concretions in marblilike clusters and wood fragments throughout. Forms wide valley.

Sandstone, brownish-black, medium-grained, friable; contains hard ledges. Forms scattered black buttes.

SECTION 13.—*Jilh al 'Ishar*—Continued

Upper *Jilh* Formation (184.0 m thick)—Continued

4. Sandstone (117.8 m thick)—Continued

Limestone, brown to golden-brown, slabby- to blocky-weathering, tight; forms prominent dip slope.

Siltstone and shale.

Sandstone, gray to tan, friable; small concretions and molds of fossil wood.

Siltstone and mudstone, greenish-gray; thin limestone bed near middle.

Sandstone, gray, friable, fine-grained, crossbedded.

Shale.

Sandstone, gray, blocky-weathering.

Shale, variegated; grades to red at base and includes some sandstone.

Sandstone, dark-brown, tightly cemented, fine- to medium-grained, crossbedded; upper 2.0 m calcareous, forms ledge and prominent dip slope.

Covered; probably shale.

Sandstone, tan, well-cemented, fine-grained; numerous small concretions.

Claystone, yellow.

Sandstone, tan, well-cemented.

Shale, olive-green.

Sandstone, tan, fine-grained; occasional thin interbeds of siltstone.

Lower *Jilh* Formation (142.1 m thick):

3. Limestone and marl (35.7 m thick):

Limestone, tan to brown, tight, brittle, blocky-weathering, fossiliferous; thin bed of calcareous sandstone at top. Cape escarpment and forms dip slope.

Marl, yellow; some shale and rare fossils.

Limestone, light-brown, tight, blocky- and slabby-weathering; some fossil casts. Forms prominent dip slope east of main scarp.

Limestone, yellowish-brown, tight, slabby-weathering, fine-grained; forms top of *Jilh* escarpment. Lower 1.0 m sandy.

Sandstone, reddish-brown, in part marly, commonly crossbedded, fine- to medium-grained.

Marl and marly limestone.

Sandstone, dark-brown, fine-grained, micaceous; forms weak ledge.

Marl; thinly interbedded marl and marly limestone.

Limestone; alternating gray tight fine-grained limestone and soft shaly limestone; occasional bone fragments.

2. Shale (25.6 m thick):

Shale, olive-green.

Limestone, gray-brown, fine-grained.

Shale, gray-green.

Limestone, gray-brown, tight, blocky-weathering; fossil casts. Forms weak bench.

Shale, green, gypsiferous.

Gypsum, white to red; streaks of red limestone.

Shale, green, very gypsiferous.

Thickness
(meters)

2.0

2.0

11.4

3.5

3.4

2.0

3.0

6.8

12.2

3.0

0.5

2.0

1.0

2.1

3.4

1.0

2.0

2.1

3.4

0.3

8.0

2.0

3.4

3.0

4.0

0.5

1.0

0.5

2.0

3.4

1.5

3.5

2.5

4.0

1.0

1.5

0.5

5.0

50.0

9.5

4.1

0.3

3.9

0.3

3.4

0.5

3.4

SECTION 13.—*Jilh al 'Isahr*—Continued

Lower Jilh Formation (142.1 m thick)—Continued	Thickness (meters)
2. Shale (23.6 m thick)—Continued	
Shale, green, gypsiferous.....	1.7
Limestone, brown-stained, tight, blocky- weathering; forms weak bench.....	0.2
Shale, green, gypsiferous.....	2.2
Sandstone, well-bedded, fine-grained; base ripple marked.....	0.7
Shale, dark-green; some fine-grained sand- stone. Upper 0.5, gypsiferous.....	3.2
Limestone, brown; fossil casts. Forms prom- inent bench.....	0.4
Limestone, soft, marly.....	1.0
Limestone, brown; fossil casts.....	0.3
1. Sandstone and shale (80.8 m thick):	
Shale, light-green.....	3.6
Sandstone, light-gray, friable, fine-grained..	3.4
Sandstone, iron-stained, ripple-marked, slabby-weathering, fine-grained; small con- cretions common.....	4.0
Shale; reddish-brown shale and sandy shale..	1.7
Sandstone, fine-grained.....	1.5
Shale and sandstone; thinly interbedded green shale, finely sandy shale, and fine-grained sandstone.....	3.5
Shale, light-green, sandy.....	1.5
Sandstone, tightly cemented, medium- grained.....	0.1
Shale, dark-green.....	1.2
Sandstone, soft, shaly.....	0.5
Sandstone, slabby-weathering, iron-stained- Shale, light-green.....	0.1
Sandstone, well-cemented, iron-stained, me- dium-grained; small concretions.....	2.1
Sandstone, friable, fine-grained; some gypsum and green shale.....	0.2
Sandstone, gray, medium-grained; small con- cretions.....	2.7
Claystone, green; some finely interbedded sandstone.....	0.3
Sandstone, light-gray, slightly iron-stained, thinly bedded.....	2.6
Claystone and sandstone; green claystone and fine-grained sandstone.....	0.4
Sandstone, black, slabby-weathering, iron- stained, well-cemented; common minute ferruginous concretions.....	2.3
Shale, dark-green, sandy.....	0.5
Sandstone, slabby-weathering, iron-stained, medium-grained; lower part ripple marked..	2.0
Sandstone, light-gray, porous, friable, fine- to medium-grained; small concretions and some greenish clay.....	1.0
Unexposed; probably mainly sandstone.....	4.5
Total thickness of Jilh Formation.....	41.1
Sudair Shale.....	326.1

SECTION 14.—*Khsham al Manjūr*

[Generalized section of Jilh Formation west of Khsham al Manjūr; R. A. Bramkamp and S. B. Henry, 1949]

Sandstone of Minjur Sandstone (Upper Triassic).	Thickness (meters)
Jilh Formation:	
Sandstone, yellow-brown, strongly calcareous, me- dium-grained, locally oolitic; rare, poorly preserved fossils. Forms main cap of upper Jilh escarpment.	2.0

SECTION 14.—*Khsham al Manjūr*—Continued

Jilh Formation—Continued	Thickness (meters)
Sandstone, buff to brown, crossbedded, fine-to coarse- grained; local layers of ironstone. Upper part strongly calcareous and slabby weathering; middle part poorly exposed, probably includes silty sand- stone and sandy shale.....	38.5
Sandstone, buff to brown, strongly crossbedded, fine- to coarse-grained; many well-laminated lenticular lenticles and platy masses of black ironstone. Layers with concentrations of quartz pebbles common.....	27.0
Dolomite, golden-tan, strongly ocherous and sandy, finely crystalline; forms weak bench.....	0.5
Sandstone, light-brown, massive, friable, medium- grained; common interbeds of red and green, gypsiferous shale and silty sandstone. Few beds are poorly exposed or covered.....	22.0
Sandstone, light-brown, crossbedded, medium-to coarse-grained; few streaks with common quartz pebbles up to 8mm in diameter. Upper 1.0 m irregularly stained red. Thin bed of red and green gypsiferous shale near base.....	29.0
Covered; thickness calculated.....	25.5
Sandstone, light-brown to off-white, fine-to medium- grained, crossbedded; exposed in pediment and thickness calculated.....	12.0
Covered; thickness calculated. A few 0.5-m beds of gray to tan, purple-weathering, commonly sandy, tight, finely crystalline limestone form very weak cuestas. Remainder of interval unexposed except for two small ledges of brown well-cemented, fine- to medium-grained sandstone.....	133.0
Total thickness of Jilh Formation.....	289.5
Sudair Shale.....	

SECTION 15.—*Ad Duwayh*

[Generalized section of Jilh Formation near Ad Duwayh; A. F. Poonce and R. F. Kopp, 1949]

Sandstone of Minjur Sandstone (Upper Triassic).	Thickness (meters)
Jilh Formation:	
Sandstone and shale; approximately equal amounts of off-white to brown, fine-to medium-grained, mod- erately sorted, commonly crossbedded, rarely calcareous, gypsiferous, and silty sandstone and mustard to greenish-yellow, soft, commonly gypsiferous shale. Thin beds of gray to tan, tight, platy-weathering, commonly sandy and impure, very finely crystalline limestone are scattered throughout interval.....	120.0
Limestone and siltstone; approximately equal amounts of complexly interbedded, light-brown, platy, impure and sandy, rarely fossiliferous lime- stone and gray, yellow and green, in part gypsif- erous siltstone. Occasional thin beds of gypsif- erous shale and gray sandstone.....	48.0
Sandstone, tan, well-sorted, fine-to medium-grained, angular, slightly gypsiferous.....	12.0
Shale, gray, friable, gypsiferous.....	7.0
Covered; thickness calculated.....	45.0
Total thickness of Jilh Formation.....	232.0
Covered.....	

SECTION 16.—*Ayn Ibn Fuhayd*

[Generalized section of Jilh Formation near 'Ayn Ibn Fuhayd: A. F. Pocock and R. P. Kopp, 1940]

Sandstone of Minjur Sandstone (Upper Triassic).

Jilh Formation:

	Thickness (meters)
Gypsum, gray to white, thin-bedded, in part poorly exposed; occasional thin beds of gray to tan, platy, impure, finely crystalline limestone and dolomite. Some sandstone and shale occurs in upper part. Interval is capped by very thin bed of tan to brick-red oolitic sandstone and oolite—same unit typically caps Jilh at other localities.	78.0
Marl, limestone and shale; in part poorly exposed but largely complexly interbedded tan to gray platy sandy marl, tan to reddish-brown thin-bedded, commonly detrital-oolitic limestone, and gray-green gypsiferous shale. Tan to light-gray sandstone, in part calcareous, occurs at several levels but becomes more common in lower part.	166.0

Total thickness of Jilh Formation..... 244.0

Covered.

SECTION 17.—*Didah*

[Generalized section of Jilh Formation near Didah: A. F. Pocock and R. P. Kopp, 1940]

Sandstone of Minjur Sandstone (Upper Triassic).

Jilh Formation:

	Thickness (meters)
Limestone and shale; alternating 2- to 4-m beds of tan to brown, tight, very sandy limestone and yellow, poorly exposed silty shale and soft marl... Covered; probably shale and gypsum(?).	22.0
Limestone and shale; interval in large part poorly exposed but apparently mostly tan thin-bedded platy-weathering limestone and soft marly limestone intimately interbedded with indeterminate amounts of tan silty shale. A thin bed of red friable sandstone occurs near base.	53.0
	178.0

Total thickness of Jilh Formation..... 253.0

Crossbedded sandstone of the Sudair Shale.

MINJUR SANDSTONE SECTION

SECTION 18.—*Khashm al Khalifa*

[Minjur Sandstone type section measured and described at Khashm al Khalifa by R. A. Brankamp, S. B. Henry, S. J. Roach, R. B. Carr, and M. C. Coffield in 1951]

Shale of Marrat Formation (Lower Jurassic).

Unconformity.

Minjur Sandstone:

	Thickness (meters)
Sandstone, tan, massive; forms vertical cliff. Interval measured by theodolite.	48.0
Shale and sandstone; complexly interbedded tan to purple silty shale and tan sandstone.	4.5
Sandstone, tan, pink-stained, weakly crossbedded, medium-grained.	7.0
Silty, buff, spheroidally-weathering.	1.0
Sandstone, buff, massive, crossbedded, medium-grained.	4.8
Shale, cream, spheroidally-weathering.	1.2
Shale and sandstone; purple, tan, and gray variegated shale; several beds of buff, massive, crossbedded sandstone in lower part.	10.3

SECTION 18.—*Khashm al Khalifa*—Continued

Minjur Sandstone—Continued

	Thickness (meters)
Sandstone, tan, massive, crossbedded, medium-grained; some layers with a white earthy matrix. Common pebble-bearing beds in lower 11 m. Forms vertical cliff.	21.1
Sandstone and shale; alternating beds of tan medium-grained crossbedded sandstone and purple and cream sandy shale.	13.8
Sandstone, buff, massive, crossbedded, medium- to coarse-grained; common layers with quartz pebbles.	15.7
Sandstone and shale; complexly interbedded tan crossbedded sandstone and variegated shale.	18.5
Sandstone, buff, massive, crossbedded, medium- to coarse-grained; forms cliff.	12.3
Shale, purple, tan and gray; some shaly sandstone. About 600 m west of measured section interval is replaced by coarse-grained sandstone.	10.5
Sandstone, buff, crossbedded, moderately cemented, medium- to coarse-grained; forms weak bench.	5.4
Shale and sandstone; purple, light-gray, and tan sandy shale and thinly interbedded silty sandstone; forms weak ledge. Thin layers of ironstone common in upper part.	9.5
Sandstone- buff, moderately cemented, crossbedded, medium- to coarse-grained; forms weak ledge.	2.2
Sandstone and shale; light-gray, mottled purple, well-bedded soft silty sandstone and sandy shale; thin seam of ironstone at top.	3.5
Sandstone, light-brown, massive, strongly crossbedded, moderately cemented, coarse-grained; streaks with quartz pebbles common.	12.3
Shale and sandstone; tan and purple sandy silty shale and many thin lenses of sandstone; a thin irregular ironstone layer at top. Upper contact shows local relief as great as 3 or 4 m.	12.2
Sandstone, buff, pink-weathering, crossbedded; a thin bed of ironstone forms weak bench at top, grades laterally to shaly sandstone.	12.6
Shale, purple and gray, sandy and silty; thin beds of ironstone form weak benches 6.3 m above base and at top. Lower part grades laterally to sandstone.	9.1
Sandstone, red-brown, pink-weathering, crossbedded; locally replaced laterally by sandy shale.	11.8
Sandstone, red-brown, strongly crossbedded, friable, highly lenticular; some argillaceous silt and sandstone. Thin beds of purple and black ironstone occur at several levels.	15.5
Sandstone, red-brown, massive, highly crossbedded, friable; common layers with abundant small pebbles. In general, strongly lenticular. Light-colored argillaceous sandstone and silt occur between main lenses. A very thin purple-black ironstone layer caps unit.	3.7
Sandstone; interval calculated, mainly sandstone; some purple and gray shale.	48.5

Total thickness of Minjur Sandstone..... 315.0

Jilh Formation.

MARRAT FORMATION SECTIONS

SECTION 19.—*Khashm adh Dhîbi*

(Marrat Formation reference section measured and sampled in the face of Khashm adh Dhîbi by R. W. Powers and H. A. McClure in 1907)

Gypsum of the Dhurma Formation (Middle Jurassic).

Upper Marrat Formation (24.2 m thick):

4. Aphanitic and calcarenitic limestone:

	Thickness (meters)
Aphanitic limestone, light-brown, moderately porous, partially recrystallized, chalky; forms massive cliff.....	11.0
Aphanitic limestone, light-brown, partially recrystallized, moderately porous, rubbly-weathering, chalky; common gastropod-pelecypod debris.....	3.0
Calcarenitic and aphanitic limestone, poorly exposed, rubbly-weathering.....	4.0
Gastropod calcarenitic limestone, brown, moderately porous, chalky; 30 percent gastropod casts and common pelecypod debris.....	2.0
Limestone, poorly exposed, chalky, calcarenitic and aphanitic.....	1.6
Gastropod calcarenitic limestone, brown, moderately porous, chalky; 35 percent medium- to coarse-grained gastropod casts. Forms weak bench.....	0.4
Shale poorly exposed, mainly yellow, fossiliferous.....	1.8
Calcarenitic limestone, brown, moderately porous, chalky; 20 percent pelecypod-gastropod debris and 10 percent dark-brown medium-grained well-rounded lime-mud pellets. Forms weak bench.....	0.4

Middle Marrat Formation (41.8 m thick):

3. Shale, siltstone, and sandstone:

Shale, red.....	2.2
Covered.....	0.4
Gastropod calcarenitic limestone, brown, tight, partially recrystallized; 60 percent calcite-replaced and -in-filled gastropod-pelecypod shells set in continuous original lime-mud matrix. Caps weak bench.....	0.2
Aphanitic limestone, light-brown, moderately porous, chalky; forms weak bench.....	1.0
Shale, red; rare thin layers of green shale.....	7.5
Sandstone, reddish-brown, moderately porous, very fine grained, angular to subrounded, crossbedded, calcareous cemented, quartzose; forms prominent massive ledge.....	2.5
Shale, red; thin layers of green and yellow shale.....	7.0
Sandstone, red, silty, massively crossbedded; forms prominent ledge.....	1.0
Shale, red; rare green shale.....	15.0
Covered; probably red shale.....	5.0

SECTION 19.—*Khashm adh Dhîbi*—Continued

Lower Marrat Formation (36.5 m thick):

2. Aphanitic and calcarenitic limestone and dolomite (15.0 m thick):

	Thickness (meters)
Calcarenitic limestone, reddish-brown, tight, partially recrystallized; 15 to 20 percent gastropod-pelecypod fragments and common hexacorals.....	0.5
Aphanitic limestone, light-brown, moderately porous, partially recrystallized and partially dolomitized; pelecypod-gastropod debris common.....	2.0
Calcarenitic limestone, light-brown, moderately porous, chalky; 15 percent medium- to coarse-grained lime-mud pellets and pelecypod debris.....	2.0
Aphanitic limestone, tan, moderately porous; 5 percent pelecypod-gastropod remains and rare dolomite rhombs.....	1.5
Calcitic dolomite and aphanitic limestone; dolomite as below; common patches of essentially unaltered aphanitic limestone.....	1.5
Calcitic dolomite, reddish-brown, moderately porous, medium-grained crystalline; 20 percent original lime-mud matrix preserved in intercrystalline spaces, ghosts of replaced pellets common.....	1.0
Calcarenitic dolomite, dark-gray-brown, medium-grained crystalline, tight; ghosts of pellets common. Rock originally calcarenitic limestone.....	1.0
Dolomite, golden-brown, moderately porous, very finely crystalline, semifrangible.....	2.0
Aphanitic limestone, golden-brown, tight, partially dolomitized; 5 percent pellets and 60 percent finely crystalline dolomite rhombs scattered uniformly throughout.....	1.0
Calcarenitic dolomite, reddish-brown, tight, medium-grained, crystalline; 20 percent ghosts of replaced pellets "floating" in dolomite.....	1.0
Aphanitic limestone, reddish-brown, sandy; 50 percent medium- to coarse-grained, angular to subrounded, quartz sand grains in lime-mud matrix.....	1.5
1. Poorly exposed; sandstone, siltstone, and shale (21.5 m thick):	
Calcareous sandstone, reddish-brown, medium- to coarse-grained, well-sorted, angular to subangular, quartzose; 30 percent reddish-brown carbonate cement. Quartz sand grains not in contact with each other suggesting sand deposited concurrently with intergranular lime-mud matrix.....	2.5
Poorly exposed; scarce exposures indicate complexly interbedded sandstone, siltstone, and shale.....	7.5
Aphanitic limestone, golden-brown, tight, partially recrystallized; forms weak bench. Lateral continuity indicates this bed definitely in place on scree-covered slope.....	0.5

SECTION 19.—*Khashm adā Dhīb*—Continued

Lower Marrat Formation (36.5 m thick)—Continued
 1. Poorly exposed; sandstone, siltstone, and shale (21.5 m thick)—Continued

	Thickness (meters)
Sandstone, greenish-gray, moderately porous, well-sorted, medium- to coarse-grained, subrounded, quartzose.....	1.0
Poorly exposed; comparison with adjacent sections shows interval to be mostly green to olive-green shale.....	9.0
Sandy pellet calcarenitic limestone, golden-brown, fine- to coarse-grained; 40 percent well-rounded fine-grained lime-mud pellets and 30 percent medium- to coarse-grained, angular to subrounded quartz sand. Forms weak ledge.....	1.0

Total thickness of Marrat Formation... 102.5

Minjur Sandstone.

SECTION 20.—*Khashm al Jufayr*

[Generalized section of Marrat Formation at Khashm al Jufayr; Max Steinake, R. A. Brankamp, E. L. Berg, R. L. Myers, and W. T. Short, 1946]

Gypsum and shale of Dhurma Formation (Middle Jurassic).

Marrat Formation:

	Thickness (meters)
Upper Marrat (22.3 m thick):	
Limestone, tan, chippy-weathering; several beds with abundant limonitic and phosphatic nodules. Forms prominent cliff.....	8.0
Poorly exposed; mainly olive-green and tan shale; well-preserved ammonites 2.0 m from base.....	7.0
Limestone and shale; complexly interbedded golden-tan chippy-weathering fossiliferous limestone and tan to olive-green shale. Basal shale bed contains well-rounded limestone pebbles.....	7.3
Middle Marrat (34.5 m thick):	
Shale, red and brown, rarely green; few very thin beds of fine-grained sandstone.....	4.5
Sandstone, red to brown, thinly bedded, micaceous and silty; occasional thin beds of red shale.....	16.5
Shale, red, silty; in part poorly exposed.....	13.5

Lower Marrat (35.0 m thick):

Dolomite and limestone; equal amounts of interbedded gray to tan, tight, fossiliferous limestone and brown, impure, finely crystalline dolomite; sand grains common in lower bed. Poorly preserved fossils including ammonites, brachiopods and echinoids common.....	10.2
Shale and sandstone, complexly interbedded; red and green shale and golden-tan, ocherous, limonite-stained, poorly cemented quartz sandstone, shaly sandstone, and sandy siltstone; common gypsum veinlets in upper part.....	12.2
Limestone, brick-red, blocky-weathering, slightly sandy, tight, aphanitic; forms weak ledge.....	0.6
Shale, green to yellow, occasionally red; thin beds of tan, slightly sandy limestone near the middle.....	12.0

Total thickness of Marrat Formation..... 91.8

Minjur Sandstone.

SECTION 21.—*Khashm al Manjūr*

[Generalized section of Marrat Formation at Khashm al Manjūr; R. A. Brankamp, E. L. Berg, R. L. Myers, and W. T. Short, 1946]

Covered; presumably shale of the Dhurma Formation (Middle Jurassic).

Marrat Formation:

	Thickness (meters)
Upper Marrat (15.8 m thick):	
Limestone, tan to yellow, rubbly-weathering, chalky, aphanitic; abundant limonite and phosphatic nodules. Thin beds of tan marly shale cap interval. Forms prominent bench.....	8.3
Shale and limestone; dominantly green to tan shale with subordinate interbeds of golden-brown, ocherous aphanitic limestone; abundant limonitic and phosphatic ooliths in upper part, rare marine fossils.....	7.5
Middle and lower Marrat undifferentiated (34.1 m thick):	

Sandstone, partially covered, reddish-brown, massive, micaceous and silty, moderately cemented; occasional beds of reddish-brown siltstone.....	23.4
Shale; mostly covered but local exposures of red silt shale.....	8.7
Dolomite, yellow to tan, impure, finely crystalline.....	2.0

Total thickness of Marrat Formation..... 49.9

Minjur Sandstone.

SECTION 22.—*Khashm Māwān*

[Generalized section of Marrat Formation at Khashm Māwān; R. A. Brankamp and H. A. Kimball, 1946]

Sandstone and Shale of Dhurma Formation (Middle Jurassic).

	Thickness (meters)
Marrat Formation:	
Sandstone, red to brown; alternately strongly and weakly cemented; strongly cemented layers form prominent ledges with intervening softer beds recessed.....	28.2
Shale, light-gray, tan, dark-red, sandy.....	4.0
Sandstone, brick-red, friable, in part crossbedded, fine- to coarse-grained; rare shale, quartz pebbles in lower part.....	4.7

Approximate total thickness of Marrat Formation..... 36.9

Minjur Sandstone.

SECTION 23.—*Mardāh and vicinity*

[Generalized section of Marrat Formation in vicinity of Mardāh; D. A. Holm and A. P. Pocock, 1947 and R. A. Brankamp, S. B. Henry and N. J. Sander, 1949]

Shale of Dhurma Formation (Middle Jurassic).

Marrat Formation:

	Thickness (meters)
Upper Marrat (20.5 m thick):	
Limestone, tan, chippy- to slabby-weathering, compact, in part fossiliferous and detrital.....	20.5
Middle Marrat (57.0 m thick):	
Shale, reddish-brown, in part micaceous and silty; subordinate interbeds of red-brown fine-grained sandstone.....	57.0

SECTION 23.—*Marrat and vicinity*—Continued

Marrat Formation—Continued		Thickness (meters)
Lower Marrat (33.3 m thick):		
Limestone, reddish-tan, thin-bedded; forms caprock of basal Marrat scarp.....	4.4	
Sandstone, yellowish-green, friable, limonitic...	1.1	
Limestone, tan, thin-bedded, impure.....	0.8	
Dolomite, light-gray, medium-bedded, sandy...	0.9	
Sandstone and shale; interbedded tan friable, in part calcareous sandstone and sandy shale...	1.9	
Limestone, yellow, tan, and rarely purple-red, alternating hard- and soft-bedded, in part dolomitic; occasional shale interbeds.....	21.2	
Shale, gray to tan.....	2.4	
Limestone, tan, compact, thinly bedded.....	0.6	
Total thickness of Marrat Formation.....	110.8	
Minjur Sandstone.		

DHURMA FORMATION SECTIONS

SECTION 24.—*Khashm adh Dhbt and eastward*

[Dhurma Formation reference section remeasured and described by R. W. Powers and H. A. McClure in 1962 in the vicinity of the original type section. The new measurement was computed from three increments between Khashm adh Dhbt and the Tuwaig Mountain Limestone escarpment about 21 km eastward.]

Limestone of the Tuwaig Mountain Limestone (Upper Jurassic).

Upper Dhurma Formation (89.0 m thick):

10. Hiyani Member (64.0 m thick)		Thickness (meters)
Shale, poorly exposed, olive-tan, calcareous.	1.8	
Pellet calcarenitic limestone, tan, moderately porous, chalky; 30 percent very fine grained, well-rounded aggregate pellets, 20 percent algal(?) trash, and 10 percent calcite-replaced molluscan debris. Foraminifera common.....	0.7	
Pellet calcarenite, brown, poorly sorted, clean-washed, tightly cemented; 40 percent fine- to medium-grained aggregate pellets, 20 percent algal(?) debris, and 10 percent calcite-replaced molluscan shell fragments.....	2.0	
Coarse molluscan carbonate, reddish-brown, poorly sorted, clean-washed, strongly recrystallized; 50 percent calcite-replaced tabular fragments of pelecypod and gastropod shells admixed with 20 percent medium-grained well-rounded aggregate pellets. Foraminifera common.....	0.8	
Shale, poorly exposed, olive-brown, calcareous.....	1.4	
Calcareous limestone, as 1.5-m-thick limestone below.....	0.5	
Shale, poorly exposed, olive-tan, calcareous.	2.6	
Pellet calcarenitic limestone, brown, well-bedded, well-rounded, chalky; 40 percent medium- to coarse-grained aggregate pellets and abundant fragments of molluscan shells and older limestone set in original lime-mud matrix.....	1.5	
Shale, poorly exposed, olive-tan.....	5.4	
Molluscan calcarenitic limestone, as 1.4-m-thick limestone below.....	0.5	

SECTION 24.—*Khashm adh Dhbt and eastward*—Continued

Upper Dhurma Formation (89.0 m thick)—Continued		Thickness (meters)
10. Hiyani Member (64.0 m thick)—Continued		
Shale, poorly exposed, olive-tan, calcareous; possible thin interbeds of soft chalky aphanitic limestone.....	3.6	
Molluscan calcarenitic limestone, as 1.4-m-thick limestone below.....	0.4	
Shale, poorly exposed, tan to olive-tan, calcareous, some very thin interbeds of chalky aphanitic limestone.....	1.6	
Molluscan calcarenitic limestone, brown, moderately porous, chalky; 25 percent medium-grained to gravel-size, tabular fragments of pelecypod and gastropod shells. Medium-grained well-rounded aggregate pellets common.....	1.4	
Shale, poorly exposed, olive-tan, calcareous. Pellet calcarenite, brown, well-sorted, very fine to fine-grained, well-rounded, laminated, tightly cemented; composed dominantly of fine-grained aggregate pellets. Rare pelecypod and echinoid debris.....	0.7	
Aphanitic limestone, golden-tan, moderately porous, chalky; 5 percent molluscan debris and scattered, finely crystalline dolomite rhombs.....	1.0	
Pellet calcarenitic limestone, tan, moderately porous, chalky; 30 percent yellow, in part superficially coated, medium-grained well-rounded aggregate pellets. Molluscan debris and Foraminifera common.....	1.0	
Aphanitic limestone, brown, moderately porous, chalky; rare molluscan debris and aggregate pellets.....	0.7	
Shale, poorly exposed, tan to olive-tan.....	7.6	
Pellet calcarenite, brown, well-sorted, well-rounded, very fine grained, tightly cemented; almost exclusively fine-grained aggregate pellets. Patches of tan chalky aphanitic limestone common.....	0.5	
Shale, poorly exposed, olive-tan.....	4.4	
Molluscan-pellet calcarenite, dark-red, poorly sorted, angular to well-rounded clean-washed, tightly cemented; 30 percent replaced molluscan shells set in a strongly recrystallized matrix of red fine-grained well-rounded pellets. Common echinoid debris and fragments derived from older limestone.....	0.5	
Shale, poorly exposed, olive-tan.....	3.3	
Calcareous limestone, brown, moderately porous, chalky; 20 percent coarse-grained to gravel-sized, commonly calcite-replaced fragments of molluscan shells. Abundant fine- to medium-grained, well-rounded aggregate pellets. Isolated pockets of fine-grained well-sorted, tightly cemented, clean-washed pellet calcarenite. Abundant <i>Gryphaea costellata</i>	3.7	
Shale, poorly exposed, olive-tan.....	8.6	

SECTION 24.—*Khashm adh Dhbi and eastward*—Continued
 Upper Dhurma Formation (80.0 m thick)—Continued
 10. Hsyan Member (64.0 m thick)—Continued

	Thickness (meters)
Coarse molluscan carbonate, brown, very poorly sorted, strongly recrystallized, tightly cemented; almost exclusively pelecypod and gastropod debris. Most original molluscan shell material now replaced by clear, coarsely crystalline calcite in crystallographic continuity with secondary intergranular cement. Molluscan debris commonly preserved as internal molds of lime mud.....	0.5
Covered; probably olive-tan shale.....	2.4
Molluscan calcarenitic limestone, reddish-brown, tight, partially dolomitized; 60 percent calcite-replaced, medium- to coarse-grained, angular fragments of molluscan shells. Common unidentifiable fine-grained organic debris.....	0.5
Covered; probably olive-tan shale.....	1.8
9. 'Atash Member (25.0 m thick):	
Calcarenitic limestone, tan, moderately porous, chalky; 20 percent medium- to coarse-grained, angular, calcite-replaced molluscan shell debris. Rare aggregate pellets.....	3.0
Aphanitic limestone, light-brown, moderately porous, chalky; calcite-replaced fragments of molluscan shells common.....	1.5
Residual coral, brown, strongly recrystallized; dominant constituent is in situ hexacorals. Interseptal space packed with lime mud and original calcareous shell material now altered to clear crystalline calcite. Common mud-filled molluscan shells.....	1.5
Calcarenitic limestone, light-brown, moderately porous, chalky; 15 percent fine- to medium-grained, well-rounded aggregate pellets and 5 percent algal(?) and molluscan debris.....	2.0
Aphanitic limestone, light-brown, moderately porous, chalky; common angular, fine- to coarse-grained calcite-replaced fragments of pelecypod shells and corals.....	2.0
Pellet calcarenitic limestone, reddish-brown, moderately porous, chalky; 25 percent red to yellow, very fine- to coarse-grained, well-rounded aggregate pellets, 10 percent coarse-grained algal debris and pelecypod fragments. Few isolated colonial coral heads.....	1.5
Aphanitic limestone, light-brown, moderately porous, partially recrystallized.....	1.2
Calcarenitic limestone, light-brown, moderately porous, chalky; 15 percent fine- to medium-grained aggregate pellets and 5 percent medium- to coarse-grained, well-rounded fragments of older aphanitic limestone, molluscan debris and algal trash.....	1.1

SECTION 24.—*Khashm adh Dhbi and eastward*—Continued
 Upper Dhurma Formation (80.0 m thick)—Continued
 9. 'Atash Member (25.0 m thick)—Continued

	Thickness (meters)
Oolite-detrital calcarenite, brown, poorly sorted, tightly cemented; 30 percent medium- to coarse-grained, well-rounded, superficial oolites and 25 percent medium-grained to gravel-sized, angular fragments of aphanitic limestone derived from older rock. Common algal(?) debris.....	1.2
Pellet calcarenitic limestone, light-brown, moderately porous, chalky; 30 percent fine- to coarse-grained, well-rounded aggregate pellets and 10 percent calcite-replaced molluscan debris. Rare algal(?) fragments and isolated pockets of clean, current-washed calcarenite.....	2.0
Calcarenitic limestone, golden-brown, sandy, moderately porous, chalky; 10 percent medium-grained aggregate pellets and abundant molluscan debris. <i>Gryphaea costellata</i>	2.0
Aphanitic limestone, tan, soft, rubbly-weathering, chalky; lenses of biogenic calcarenitic limestone. <i>Gryphaea costellata</i>	3.2
Calcarenitic limestone, light-brown, moderately porous, chalky; 20 percent fine- to medium-grained, well-rounded aggregate pellets and 20 percent coarse-grained, well-rounded acorn-shaped algal(?) debris. Abundant molluscan shell fragments and rare Foraminifera. Bed contains isolated patches of clean, current-washed, tightly cemented pellet calcarenite. <i>Gryphaea costellata</i>	2.8
Middle Dhurma Formation (164.7 m thick):	
8. <i>Dhurmaites</i> zone (54.0 m thick):	
Algal(?) calcarenite, brown, moderately sorted, well-bedded, fine- to coarse-grained well-rounded, tightly cemented; 30 percent acorn-shaped coarse-grained algal(?) debris 20 percent fine- to medium-grained, well-rounded aggregate pellets, and 10 percent angular to well-rounded fragments of older limestone, molluscan debris and Foraminifera common caps prominent bench.....	1.5
Aphanitic limestone, light-brown, moderately porous, chalky; 5 percent medium-grained well-rounded pellets and molluscan debris.....	1.5
Poorly exposed; probably tan soft chalky aphanitic limestone and marl with thin interbeds of calcarenitic limestone.....	13.9
Aphanitic limestone, tan, chippy-weathering, soft, chalky.....	3.2
Molluscan calcarenitic limestone, tan, tight; 50 percent molluscan debris and aggregate pellets. Forms weak bench.....	0.4
Aphanitic limestone, tan, tight, chippy-weathering; local layers finely pelleted and littered with organic debris. A weak ledge at top formed by very thin bed of calcarenitic limestone.....	7.6

SECTION 24.—*Khashm adh Dhūbī and eastward*—ContinuedMiddle Dhurma Formation (164.7 m thick)—Continued
8. *Dhurmaites* zone (54.0 m thick)—Continued

	Thickness (meters)
Aphanitic and calcarenitic limestone; alternating layers of cream-colored to tan, soft aphanitic limestone and hard pellet-molluscan calcarenitic limestone; weak benches 2.3 and 4.8 m above base.....	8.7
Covered.....	3.3
Poorly exposed; acree slope littered with pellet calcarenitic limestone; probably much soft marly limestone in interval.....	2.2
Aphanitic limestone, reddish-brown, tight, partially recrystallized.....	0.5
Oolite calcarenite, tan, medium-grained, moderately cemented; dominantly oolitic. Forms gentle slope above bench.....	0.8
Oolite calcarenitic limestone, brown, tight; forms prominent bench.....	1.0
Aphanitic limestone, tan, tight, partially recrystallized, brittle, fossiliferous; weathers to small irregularly shaped chips.....	2.9
Pellet calcarenitic limestone, reddish-brown, moderately porous, chalky; 30 percent fine- to medium-grained well-rounded aggregate pellets and 10 percent medium-grained angular fragments of molluscan debris.....	1.8
Pellet-molluscan calcarenitic limestone, reddish-brown, moderately porous, well-sorted, medium- to coarse-grained; 40 percent aggregate pellets and 30 percent molluscan debris set in partially dolomitized lime-mud matrix. Rare Foraminifera.....	1.2
Pellet calcarenite, reddish-brown, poorly sorted, very fine grained to fine gravel-sized, tightly cemented; 25 percent very fine to medium-grained, well-rounded, commonly superficially coated aggregate pellets, 20 percent red coarse-grained well-rounded composite grains derived from older lithified limestones, and 15 percent fine gravel-sized tabular fragments of molluscan shells.....	1.0
Calcarenitic limestone, golden-brown, moderately porous, chalky; 20 percent fine- to medium-grained, well-rounded, superficially coated, lime-mud pellets and 20 percent medium- to coarse-grained angular fragments of molluscan shells. Rare Foraminifera.....	0.8
Aphanitic limestone, brown, moderately porous, chalky, rarely pelleted.....	1.7

7. *Micromphalites* zone (32.3 m thick):

Oolite calcarenite, golden-brown, porous, poorly sorted, weakly cemented; 30 percent fine- to medium-grained well-rounded superficial ooliths, 20 percent medium-grained biserial Foraminifera, and 10 percent fragments of older limestone, molluscan debris, and echinoid spines. Top of major ledge-forming crossbedded oolite bed.....	3.5
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SECTION 24.—*Khashm adh Dhūbī and eastward*—ContinuedMiddle Dhurma Formation (164.7 m thick)—Continued
7. *Micromphalites* zone (32.3 m thick)—Continued

	Thickness (meters)
Oolite calcarenite, golden-brown, moderately porous, well-sorted, medium- to coarse-grained, well-rounded, moderately cemented; almost exclusively superficial ooliths. Rare Foraminifera.....	1.0
Oolite-molluscan calcarenite, golden-brown, moderately sorted, medium- to coarse-grained, well-rounded; 50 percent ooliths (generally superficial) and 40 percent tabular fragments of molluscan shells oriented parallel to bedding. Rare algal debris. Nuclei of ooliths almost exclusively aggregate pellets and possibly fragments of aphanitic limestone derived from older rock. Base of massive crossbedded ledge-forming oolite.....	1.0
Covered.....	11.7
Aphanitic limestone, reddish-brown to light-brown, moderately porous, chalky.....	11.8
Calcarenitic limestone, tan, tight, partially recrystallized, fossiliferous.....	0.3
Aphanitic limestone, light-brown, moderately porous, chalky; 5 percent medium- to coarse-grained well-rounded pellets and fragments of molluscan shells.....	3.0

6. *Tulites* zone (36.1 m thick):

Pellet calcarenite, golden-brown, moderately sorted, very fine- to coarse-grained, well-rounded, tightly cemented; 50 percent very fine to fine-grained well-rounded aggregate pellets, 10 percent coarse-grained to fine gravel-sized well-rounded fragments of older aphanitic limestone, molluscan debris common. Forms prominent bench.....	1.7
Pellet calcarenitic limestone, golden-brown, tight, well-sorted, medium- to coarse-grained, well-rounded; 70 percent aggregate pellets set in original lime-mud matrix. Although individual grains commonly in contact, all intergranular space is packed with lime mud. Pellets appear to be detrital fragments derived from older limestone. Molluscan debris and Foraminifera common.....	2.5
Pellet calcarenitic limestone, reddish-brown, tight, partially recrystallized; 30 percent medium- to coarse-grained well-rounded aggregate pellets commonly with superficial oolite coat, 10 percent medium- to coarse-grained well-developed ooliths. Molluscan debris common.....	1.0
Oolite calcarenitic limestone, brown, moderately porous, partially recrystallized, chalky; 15 percent medium- to coarse-grained superficial ooliths.....	1.0

SECTION 24.—*Khashm adh Dhāb and eastward*—Continued
Middle Dhurma Formation (164.7 m thick)—Continued

6. *Tulites* zone (36.1 m thick)—Continued

	Thickness (meters)
Pellet calcarenite, golden-brown, moderately sorted, well-rounded, tightly cemented; 60 percent very fine to fine-grained well-rounded aggregate pellets and 10 percent medium- to coarse-grained superficial oolites, molluscan debris commonly replaced by calcite. Rare patches of lime-mud matrix.	1.0
Calcarenitic limestone, golden-brown, moderately porous, chalky; 10 percent medium- to coarse-grained well-rounded superficial oolites and 10 percent well-rounded medium-grained aggregate pellets. Molluscan debris commonly replaced by calcite.	1.5
Aphanitic limestone, light-brown, tight, partially recrystallized; coarse-grained well-rounded aggregate pellets common.	1.5
Pellet calcarenite, light-brown, moderately sorted, very fine to medium-grained, well-rounded, tightly cemented; 60 percent aggregate pellets and 10 percent calcite replaced molluscan debris.	0.7
Aphanitic limestone, reddish-brown, tight, strongly dolomitized; 70 percent very finely crystalline dolomite rhombs irregularly scattered through lime-mud matrix.	1.6
Aphanitic limestone, light-brown, moderately porous, chalky; rare pockets of clean, current-washed, tightly cemented pellet calcarenite.	4.1
Oolite calcarenite limestone, tan, moderately porous, strongly recrystallized; 50 percent medium- to coarse-grained well-rounded superficial oolites and rare molluscan debris.	3.0
Pellet calcarenite, golden-brown, well-sorted, very fine grained, well-rounded, tightly cemented; dominantly aggregate pellet, some fine- to medium-grained fragments of molluscan shells and very rare coarse-grained, well-developed oolites.	1.0
Pellet calcarenite limestone, brown, moderately porous, chalky; 30 percent very fine grained, well-rounded aggregate pellets, rare calcite-replaced pelecypod shells.	1.0
Aphanitic limestone, reddish-brown, tight, strongly recrystallized, in part siliceous.	2.0
Pellet calcarenite, reddish-brown, well-sorted, dominantly fine grained, moderately cemented and porous; mostly aggregate pellets, molluscan fragments common.	3.5
Aphanitic limestone, light-brown, moderately porous, chalky; 5 percent calcite-filled outlines of monaxon sponge spicules, calcite-replaced fragments of molluscan shells common, rare aggregate pellets and pockets of clean, current-washed, tightly cemented pellet calcarenite.	1.8

SECTION 24.—*Khashm adh Dhāb and eastward*—Continued
Middle Dhurma Formation (164.7 m thick)—Continued

6. *Tulites* zone (36.1 m thick)—Continued

	Thickness (meters)
Pellet calcarenite, golden-brown, well-sorted, well-rounded, fine- to medium-grained, tightly cemented; 10 percent coarse-grained fragments of pelecypod shells.	0.4
Calcarenitic limestone, golden-brown, moderately porous, chalky; 20 percent medium-grained, well-rounded, aggregate pellets and 20 percent medium-grained molluscan shell debris.	1.3
Aphanitic limestone, poorly exposed, tan, soft, chalky.	1.2
Pellet calcarenite, tan, well-sorted, very fine grained, tightly cemented; mainly aggregate pellets, superficial oolites and organic debris common. Forms ledge.	0.5
Calcarenitic limestone, tan, moderately porous, soft, chalky; 20 percent superficial oolites and aggregate pellets.	1.6
Algal(?) molluscan calcarenite, golden-brown, very poorly sorted, fine- to coarse-grained to gravel-sized, well-rounded to tabular, tightly cemented; 25 percent coarse-grained, irregularly shaped algal(?) debris, 25 percent molluscan fragments (pelecypod dominant), and 20 percent fine- to medium-grained aggregate pellets.	1.2
Pellet calcarenite, brown, well-sorted, medium-grained, well-rounded, tightly cemented; dominant constituent is aggregate pellets, rare well-developed, coarse-grained oolites.	1.0
5. <i>Thambites</i> zone (42.3 m thick):	
Covered.	1.1
Pellet calcarenite, golden-brown, well-sorted, medium-grained, tightly cemented; forms prominent bench.	1.7
Pellet calcarenite limestone, brown, chalky.	1.5
Pellet calcarenite and pellet calcarenite limestone; complexly interbedded, golden-brown, well-sorted, medium- to coarse-grained, tightly cemented pellet calcarenite and light-brown aggregate pellet calcarenite limestone. Molluscan debris and algal(?) fragments common, grains commonly coated with single oolitic layer.	1.0
Pellet-molluscan calcarenite, golden-brown, moderately sorted, porous, fine- to medium-grained, poorly cemented.	1.2
Aphanitic limestone, brown, moderately porous, soft, chalky; single ammonite.	1.5
Pellet calcarenite, golden-brown moderately sorted, fine- to coarse-grained, well-rounded tightly cemented; 50 percent lime-mud pellets and 20 percent coarse-grained tabular fragments of pelecypod shells, rare superficial oolite coating on some pellets and tabular nuclei.	4.5

SECTION 24.—*Khashm adh Dhbi and eastward*—Continued

Middle Dhurma Formation (164.7 m thick)—Continued

5. *Thambites* zone (42.3 m thick)—Continued

	Thickness (meters)
Pellet calcarenitic limestone, light-brown, tight, partially recrystallized; 40 percent fine- to medium-grained aggregate pellets, abundant Foraminifera, and replaced molluscan debris. Patches of clean, current-washed, tightly cemented pellet calcarenite common.....	2.1
Pellet-molluscan calcarenite, reddish-brown poorly sorted, fine-grained to gravel-sized, tightly cemented; 40 percent fine- to coarse-grained, well-rounded lime-mud pellets and 30 percent molluscan shell debris set in pellet calcarenite matrix, Foraminifera common.....	0.5
Pellet calcarenite and pellet calcarenitic limestone; golden-brown, moderately porous, fine- to medium-grained pellet calcarenitic limestone intimately admixed with pellet calcarenite; calcarenitic limestone is soft and chalky; pellet calcarenite is hard and tightly cemented. Foraminifera common.....	1.3
Pellet calcarenite, golden-brown, moderately sorted, fine- to coarse-grained, tightly cemented, well-rounded; 60 percent aggregate pellets, 10 percent calcite-replaced, angular fragments of molluscan shells, and rare Foraminifera.....	0.6
Pellet calcarenitic limestone, tan, tight partially recrystallized; 30 percent fine- to medium-grained, well-rounded aggregate pellets, abundant Foraminifera and calcite replaced pelecypod shells. Isolated patches of tightly cemented, clean, current-washed calcarenite common.....	1.5
Pellet calcarenite, golden-brown, moderately sorted, medium- to coarse-grained, well-rounded, tightly cemented; 70 percent aggregate pellets, abundant coarse-grained fragments of calcite-replaced molluscan debris.....	1.5
Calcarenitic limestone, brown, soft, marly; few fossils including ammonite in lower part.....	1.7
Pellet calcarenitic limestone, light-brown, tight, poorly sorted; 30 percent fine- to medium-grained, well-rounded aggregate pellets, 10 percent coarse-grained, calcite-replaced, angular fragments of molluscan shells, Foraminifera common and pockets of clean, current-washed, fine- to coarse-grained, tightly cemented pellet calcarenite.....	2.5
Pellet calcarenite, golden-brown, fine- to medium-grained, well-sorted, tightly cemented; 50 percent fine- to medium-grained aggregate pellets, 10 percent molluscan debris, rare Foraminifera.....	1.3

SECTION 24.—*Khashm adh Dhbi and eastward*—Continued

Middle Dhurma Formation (164.7 m thick)—Continued

5. *Thambites* zone (42.3 m thick)—Continued

	Thickness (meters)
Pelecypod-pellet calcarenite, reddish-brown, moderately sorted, dominantly medium- to coarse-grained, tabular to well-rounded, tightly cemented; 40 percent coarse-grained tabular fragments of pelecypod shells, 30 percent fine- to medium-grained, well-rounded aggregate pellets and rare Foraminifera.....	0.8
Aphanitic limestone and pellet calcarenite, brown, complexly interbedded pellet calcarenite and aphanitic limestone.....	0.5
Aphanitic limestone, tan, moderately porous, chalky; 5 percent fine- to medium-grained, well-rounded lime-mud pellets and molluscan debris, rare Foraminifera.....	1.4
Pellet calcarenite, golden-brown, well-sorted, fine- to medium-grained, well-rounded, tightly cemented; 70 percent aggregate pellets, rare Foraminifera and pelecypod fragments. Forms weak bench.....	0.6
Pellet calcarenitic limestone, light-brown, tight; 40 percent fine- to medium-grained, well-rounded lime-mud pellets, common pockets of clean, current-washed, well-rounded, fine- to medium-grained, tightly cemented pellet calcarenite, Foraminifera common, and rare fragments of molluscan shells.....	0.4
Aphanitic limestone, brown, tight, partially recrystallized; 5 percent very fine- to medium-grained aggregate pellets, Foraminifera and molluscan debris.....	0.8
Pellet calcarenite, brown, moderately sorted, well-rounded, tightly cemented, fine- to coarse-grained; 60 percent fine- to medium-grained, well-rounded aggregate pellets, and abundant molluscan debris and Foraminifera.....	2.0
Covered.....	3.5
Pellet calcarenite, golden-brown, well-sorted, medium- to coarse-grained, well-rounded, tightly cemented; 60 percent aggregate pellets. Foraminifera common, algal debris, and molluscan fragments.....	2.1
Algal calcarenite, golden-brown, moderately sorted, fine- to coarse-grained, tightly cemented; dominantly medium- to coarse-grained, well-rounded to tabular algal debris; 20 percent fine- to medium-grained, well-rounded aggregate pellets, abundant angular fragments of molluscan shells and Foraminifera common.....	1.4
Covered.....	1.0
Pellet calcarenitic limestone, tan, soft, rubbly-weathering; forms weak bench.....	2.3

SECTION 24.—*Khashm adh Dhibi and eastward*—Continued

Lower Dhurma Formation (120.8 m thick):

4. *Ermoceras* zone (34.5 m thick):

	Thickness (meters)
Pellet calcarenitic limestone, golden-tan, moderately porous, chalky; 30 percent fine- to coarse-grained, well-rounded, aggregate pellets, abundant Foraminifera. Lime-mud matrix shows distinct mottled "algal" appearance. Top of Dhibi limestone, caps major cliff, and forms widespread dip slope.	0.5

Aphanitic limestone, light-brown, tight to moderately porous, partially recrystallized, chalky; abundant medium-grained pellets, gravel-sized algal nodules, and calcite blebs filling disrupted lime mud. Foraminifera common.	5.0
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Pellet calcarenitic limestone, light-brown, tight, partially recrystallized; 30 percent fine- to coarse-grained, well-rounded, aggregate pellets; common "birdseye" texture with mud apparently of algal origin or algal-bound. Foraminifera and stylolites common.	1.0
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Aphanitic limestone, medium-brown, tight, partially recrystallized; common gravel-sized (2.0 to 8.0 mm) algal nodules with well-developed concentric layering and common calcite-filled openings, common well-rounded, medium-grained pellets, Foraminifera, and poorly preserved brachiopods and stromatopora.	3.0
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Calcarenitic limestone, tan, tight, partially recrystallized; 20 percent light-brown, well-rounded, fine- to medium-grained pellets, Foraminifera and stylolites common.	0.5
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Base of Dhibi limestone.	18.5
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Covered.	6.0
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Shale, olive-green and golden-brown, gypsiferous.	1.5
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Shale, olive-green and golden-brown, gypsiferous.	9.7
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Impure pellet calcarenitic limestone, brown, soft, chalky; abundant aggregate pellets and some fossils.	0.3
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Shale, olive-green; some gypsum veinlets.	4.0
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Shale, olive-green, gypsiferous; common interbedded, impure aphanitic limestone, common sponges.	4.7
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2. Shale, aphanitic limestone, and calcarenitic limestone (35.6 m thick):

Impure aphanitic limestone, gray-tan, chalky; sponges common.	2.3
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Shale, olive-green, gypsiferous.	3.0
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Aphanitic limestone, light-tan, rubbly-weathering, chalky; forms weak bench.	4.0
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Pellet calcarenitic limestone, tan, moderately porous, chalky; common pellets.	2.1
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SECTION 24.—*Khashm adh Dhibi and eastward*—Continued

2. Shale, aphanitic limestone, and calcarenitic limestone (35.6 m thick)—Continued

	Thickness (meters)
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Shale, golden-brown, rarely green.	2.1
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Aphanitic limestone, gray-tan, soft, chalky.	1.3
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Covered.	1.3
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Shale, golden-brown.	1.0
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Shale, poorly exposed, green, gypsiferous; a few thin layers of chalky aphanitic limestone.	5.2
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Calcarenitic limestone, light-brown, moderately porous, chalky; 15 percent badly fragmented molluscan debris and common outlines of calcite-filled, monaxon sponge spicules. Caps moderate bench.	0.5
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Pellet calcarenitic limestone, light-brown, moderately porous, chalky; 30 percent pellets and 20 percent molluscan debris.	1.5
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Shale, green, gypsiferous.	2.7
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Molluscan calcarenitic, brown, poorly sorted, fine- to coarse-grained, tightly cemented; 30 percent gastropod-pelecypod shell debris, and abundant well-rounded aggregate pellets. Top of weak bench.	0.4
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Shale and aphanitic limestone; complexly interbedded green gypsiferous shale and gray chalky aphanitic limestone.	1.6
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Calcarenitic limestone, golden-brown, tight; 15 percent pelecypod-gastropod remains.	0.5
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Forms weak bench.	3.2
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Shale and aphanitic limestone; complexly interbedded green gypsiferous shale and gray chalky aphanitic limestone.	3.2
---	-----

Calcarenitic limestone, golden-brown, moderately porous, chalky; 20 percent strongly recrystallized pelecypod fragments.	0.6
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Aphanitic limestone, tan, tight; rare thin interbeds of green shale.	2.3
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1. <i>Dorsatensis</i> zone (30.5 m thick)	1.5
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Sandstone, green, silty, gypsiferous; very rare, tan aphanitic limestone.	0.3
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Aphanitic limestone, pink, tight, partially recrystallized.	0.1
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Shale, green, gypsiferous.	2.0
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Aphanitic limestone, tan, moderately porous, chalky.	2.8
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Shale, green; veined with gypsum.	1.0
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Pellet calcarenitic limestone, brown, moderately porous, fine- to medium-grained.	1.0
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Calcarenitic, reddish-brown, porous, weakly cemented; dominantly white, cylindrical organic remains of unknown origin.	1.6
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Shale, green and purple, gypsiferous.	0.2
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Aphanitic limestone, brown, moderately porous, chalky.	1.0
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Shale, green and purple, gypsiferous.	0.7
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Pellet calcarenitic, dark-brown, porous, strongly recrystallized, fine-grained, moderately cemented; entire bed recrystallized to finely crystalline calcite mosaic; however, original texture still readily visible.	0.7
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Forms weak ledge.	
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SECTION 24.—*Khashm adh Dhibi and eastward*—Continued

Lower Dhurma Formation (120.8 m thick)—Continued	
1. <i>Dorsetensis</i> zone (30.5 m thick)—Continued	
Shale, yellow, calcareous.....	1.3
Sandstone, yellow, calcareous; few poorly preserved fossils.....	0.2
Shale, green, gypsiferous.....	1.0
Aphanitic limestone, brown, moderately porous, chalky.....	0.1
Shale, green, gypsiferous.....	0.5
Coarse molluscan calcarenitic limestone, reddish-brown, poorly sorted, sandy, partially dolomitized; 60 percent gravel-sized, gastropod-pelecypod mixture set in an almost completely dolomitized matrix of lime mud.....	0.6
Covered.....	0.5
Shale, yellowish-green, gypsiferous.....	0.3
Aphanitic limestone, reddish-brown, moderately porous, partially dolomitized.....	0.1
Shale, purple, sandy, gypsiferous.....	0.6
Shale, yellowish-green, gypsiferous.....	0.6
Calclitic dolomite, reddish-brown, very finely crystalline, moderately porous, calcitic; 20 percent original lime-mud matrix still preserved between dolomite crystals. Forms top of small rounded hill.....	0.2
Shale, yellowish-tan, in part calcareous.....	4.0
Gypsum, varicolored; subordinate green and purple shale.....	1.8
Oolitic calcarenite, gray-brown, well-sorted, tightly cemented, medium- to coarse-grained; 60 percent well-developed ooliths admixed with some internally structureless aggregate to pellets.....	0.1
Gypsum, varicolored.....	2.5
Aphanitic limestone, golden-brown, partially dolomitized.....	0.2
Gypsum, varicolored, well-bedded, crystalline.....	2.3
Coarse pelecypod-pellet carbonate, brown, poorly sorted, moderately cemented; 50 percent disarticulated gravel-sized pelecypod shells and some gastropod remains in a matrix of pink, very fine grained, pellet calcarenite. Forms thin bed in gypsiferous and shaly unit.....	0.2
Gypsum, varicolored, well-bedded, crystalline.....	1.2

Total thickness of Dhurma Formation... 374.5
Marrat Formation.

SECTION 25.—*Wadi Birk*

[Generalized section of Dhurma Formation at Wadi Birk; measurements by R. A. Brinkman, 1945, and R. D. Gierhart and P. R. Awerus, 1947]

Limestone of Tuwaiq Mountain Limestone (Upper Jurassic).	
Upper and middle Dhurma Formation (193.5 m thick):	
Thickness (meters)	
8. Hsiyan Member (about 56.0 m thick):	
Shale, gray-green; occasional gypsum veins and very thin beds of limestone.....	34.0
Limestone, gray, massive, marly; forms prominent cliff.....	6.0

SECTION 25.—*Wadi Birk*—Continued

Upper and middle Dhurma Formation (193.5 m thick)—Continued	
Thickness (meters)	
8. Hsiyan Member (about 56.0 m thick)—Con.	
Shale, gray-green; occasional gypsum veins and very thin beds of limestone. Base is believed to be approximate level of 'Atash-Hsiyan contact.....	16.0
7. 'Atash Member (about 19.5 m thick):	
Limestone and shale; completely interbedded tan to gray, soft, marly limestone and gray-green shale.....	9.5
Limestone, gray to brown, thin-bedded, commonly marly; a few layers of hard, platy-weathering, highly fossiliferous limestone. Fossils are mostly pelecypods.....	10.0
6. <i>Dhurmaites</i> zone (about 17.0 m thick):	
Shale, poorly exposed, gray-green, calcareous, in part gypsiferous.....	17.0
5. <i>Micromphalites</i> zone (about 21.0 m thick):	
Limestone and shale; alternating beds of gray, marly limestone and gray-green, calcareous shale.....	21.0
4. <i>Tulites</i> zone (39.5 m thick):	
Limestone, tan to brown, in part marly, rarely sandy, commonly fossiliferous; thin beds of calcarenite at several levels.....	39.5
3. <i>Thambites</i> zone (40.5 m thick):	
Limestone, poorly exposed, off-white to tan, thin-bedded, fossiliferous, aphanitic and calcarenitic.....	40.5
Lower Dhurma Formation (67.6 m thick):	
2. Post- <i>Dorsetensis</i> beds (51.3 m thick):	
Limestone, buff, tan- to gray-weathering, tight, aphanitic; massive cliff former—Dhibi limestone. Unit plus underlying interval of unknown thickness are lateral equivalent of <i>Ermaceras</i> zone.....	7.6
Covered; thin (1.0-m-thick) bed of orange-brown, strongly cemented, oolitic calcarenite in lower part.....	10.5
Sandstone, brown, moderately to well-cemented, medium- to coarse-grained, commonly silty.....	33.2
1. <i>Dorsetensis</i> zone (16.3 m thick):	
Shale and sandstone; mainly green, some red and purple shale with interbedded, gray, friable sandstone.....	3.8
Shale, yellow, red, green, purple, in part silty and sandy; a thin gray, ripple-marked ironstone layer just below top.....	4.0
Dolomite, golden-brown, soft, shaly-weathering, finely crystalline; becomes less dolomitic and oolitic near base.....	2.1
Sandstone and shale; golden-brown, ferruginous, silty and coarse-grained quartz sandstone intimately interbedded with variegated shale; single thin bed of finely crystalline dolomite near middle.....	6.4
Total thickness of Dhurma Formation... 261.1	
Marrat Formation.	

SECTION 26.—*Khashm al Jueyafah and Khashm 'Ushayrah*

[Generalised section of Dhurma Formation at Khashm al Jueyafah and Khashm 'Ushayrah; measurements by R. D. Gierhart and L. D. Owens, 1947, and R. A. Brunkamp, 1961, respectively]

Limestone of the Tuwaiq Mountain Limestone (Upper Jurassic).

Upper and middle Dhurma Formation (147.0 m thick):

- | | Thickness
(meters) |
|--|-----------------------|
| 4. <i>Dhurmaites</i> zone, Hiyay and 'Atash Members (90.1 m thick): | |
| Shale, olive-gray, in part calcareous; a few very thin layers of cream-colored to brown, soft, marly limestone in upper part. Poorly exposed interval near middle, <i>Gryphaea costellata</i> and <i>Eudesia cardium</i> common near base..... | 46.3 |
| Calcareous and limestone; intimately interbedded brown to gray, biogenic and oolitic calcarenite and calcarenite limestone; common interbedded olive-tan, silty shale. May be in part equivalent to 'Atash Member..... | 8.7 |
| Shale, poorly exposed, brown; several thin indurated layers with biogenic debris..... | 24.6 |
| Aphanitic limestone, gray-tan, compact, impure..... | 6.5 |
| Shale, yellow and olive-brown, calcareous..... | 4.0 |

- | | |
|--|------|
| 3. <i>Micromphalites</i> zone (21.8 m thick): | |
| Limestone, cream-colored to gray, compact, rubbly-weathering, aphanitic; occasional thin beds of porous, tightly cemented calcarenite. Base of unit is base of <i>Micromphalites</i> zone..... | 21.8 |

- | | |
|---|------|
| 2. <i>Thambites</i> and <i>Tulites</i> zones (35.1 m thick): | |
| Limestone, cream-colored, soft to compact, in part biogenic and oolitic; common interbeds of calcarenite limestone, single calcarenite bed at base..... | 35.1 |

Lower Dhurma Formation (about 50 m thick):

- | | |
|---|------------|
| 1. Pre- <i>Thambites</i> beds (about 50 m thick): | |
| Limestone, brown, cliff-forming; Dhibi limestone..... | 7.0 |
| Sandstone and shale; mainly white, red, and brown, coarse-grained, crossbedded sandstone; nearly one-third of interval is interbedded gray to brown, commonly sandy shale; upper part poorly exposed..... | about 43.0 |

Total thickness of Dhurma Formation..... about 197.0

Marrat Formation.

SECTION 27.—*Al Haddar*

Generalised section of Dhurma Formation at lat 21°45' N. (near Al Haddar); measurements by R. D. Gierhart and L. D. Owens, 1946]

Sandstone of Tuwaiq Mountain Limestone (Upper Jurassic).

Upper and middle Dhurma Formation:

- | | Thickness
(meters) |
|--|-----------------------|
| 3. Approximate equivalent of <i>Dhurmaites</i> zone, Hiyay and 'Atash Members (about 82 m thick): | |
| Shale, gray-tan to brown; occasional thin beds of impure and fossiliferous limestone..... | 39.3 |
| Sandstone, white to gray, commonly red- and purple-mottled, in part friable; interbedded gray shale near middle..... | 29.0 |

SECTION 27.—*Al Haddar*—Continued

Upper and middle Dhurma Formation—Continued

- | | |
|---|-----------------------|
| 3. Approximate equivalent of <i>Dhurmaites</i> zone, Hiyay and 'Atash Members (about 82 m thick)—Continued | Thickness
(meters) |
| Shale, gray, calcareous, gypsiferous; a few very thick bands of fossiliferous limestone. Bracketing marker beds indicate <i>Micromphalites</i> - <i>Dhurmaites</i> contact near base of interval..... | 13.7 |
| 2. Approximate equivalent of <i>Micromphalites</i> zone (about 21.0 m thick): | |
| Shale, gray, calcareous, gypsiferous..... | 6.0 |
| Limestone, tan to brown, chippy- to rubbly-weathering, aphanitic; thin 1.0-m-thick bed of reddish-brown, calcite-cemented, silty sandstone near middle..... | 15.0 |
| 1. <i>Thambites</i> and <i>Tulites</i> zones (about 26.0 m thick): | |
| Limestone, brown and olive-green, chalky, rubbly-weathering, in part fossiliferous; becomes sandy in lower part..... | 24.0 |
| Not measured; estimated 2.0 m to approximate equivalent of top of Dhibi limestone..... | 2.0 |

Total thickness of upper and middle Dhurma..... about 129.0

No data.

SECTION 28.—*Khashm ash Shajari*

[Generalised section of Dhurma Formation at Khashm ash Shajari; measurements by R. A. Brunkamp and H. A. Kimball, 1960]

Sandstone of Tuwaiq Mountain Limestone (Upper Jurassic).

Upper and middle Dhurma Formation (about 122.1 m thick):

- | | Thickness
(meters) |
|---|-----------------------|
| 4. Approximate equivalent of <i>Dhurmaites</i> zone, Hiyay and 'Atash Members (76.9 m thick): | |
| Sandstone, buff to yellowish-brown and brown, crossbedded, medium-grained, in part ferruginous; common concretionary ironstone masses, slabby black ironstone, fossil wood, and yellow, purple, and green shale..... | 76.9 |
| 3. Approximate equivalent of <i>Micromphalites</i> zone (18.3 m thick): | |
| Shale, yellowish-tan, calcareous, sandy, in part gypsiferous..... | 6.7 |
| Limestone, cream-colored, chippy-weathering, soft, impure; thin interbeds of tan gypsiferous shale. <i>Gryphaea costellata</i> near base. Base of unit corresponds to <i>Tulites</i> - <i>Micromphalites</i> contact further north..... | 11.6 |
| 2. Approximate equivalent of <i>Thambites</i> and <i>Tulites</i> zones (26.9 m thick): | |
| Sandstone, yellowish-brown, moderately cemented, medium-grained; several thin layers of tan sandy dolomite shale..... | 11.1 |
| Shale, tan, soft, sandy, dolomitic; common thin layers of tan, very soft, sandy, rubbly-weathering dolomitic limestone..... | 15.8 |

SECTION 28.—*Khashm ash Shajari*—Continued

Lower Dhurma:	Thickness (meters)
1. Approximate equivalent of Dhibi limestone (11.9 m thick):	
Sandstone, brown, massive-bedded, moderately cemented, medium-grained; forms cliff.....	11.9
Total thickness of Dhurma Formation..	134.0+
Sandstone of Dhurma Formation and (or) Minjur or Jilh Formations.	

SECTION 29.—*Khashm at Turab*

[Generalized section of Dhurma Formation near Khashm at Turab; measurements by D. A. Holm and A. F. Pocock, 1946, R. A. Bramkamp, R. C. Kerr, B. Beverly, Jr., R. D. Oberhart, and W. Dell'Ore, 1946, and R. A. Bramkamp, S. B. Henry, and N. J. Sander, 1949.]

Limestone of the Tuwaiq Mountain Limestone (Upper Jurassic).	Thickness (meters)
Upper Dhurma Formation (about 86.0 m thick):	
8. Hisyay Member (59.0 m thick):	
Shale, gray to olive-green; occasional beds of off-white, marly limestone.....	59.0
7. 'Atash Member (about 27.0 m thick):	
Not measured; but dominantly cream-colored to gray, marly, rubbly-weathering limestone; few interbeds of olive-gray gypsiferous shale. <i>Gyrphaea costellata</i> common.....	about 27.0
Middle Dhurma Formation (about 162.7 m thick):	
6. <i>Dhurmaites</i> zone (52.0 m thick):	
Covered; includes some olive-tan shale; interval capped by 1.0-m-thick bed of golden-tan, strongly cemented white calcarenite that forms prominent bench.....	10.5
Limestone, cream-colored to tan, compact, soft, rubbly-weathering, aphanitic; common interbeds throughout of brown medium-grained, tightly cemented, pellet calcarenite.....	26.2
Shale, poorly exposed, gray to olive-green, calcareous; common thin interbeds of cream-colored soft marly limestone.....	15.3
5. <i>Micromphalites</i> zone (32.7 m thick):	
Limestone, poorly exposed, cream-colored to gray, soft, marly, rubbly-weathering.....	9.0
Calcareous, tan, massive, medium-grained, tightly cemented; forms prominent bench..	7.0
Shale and limestone; poorly exposed, complexly interbedded, reddish-gray silty shale and gray-tan soft marly limestone.....	16.7
4. <i>Tulites</i> zone (38.0 m thick):	
Limestone, poorly exposed, gray to tan, soft, rubbly-weathering, chalky; occasional thin beds of brown, tightly cemented calcarenite. About one-third of interval is covered; may mask shale.....	38.0
3. <i>Thambites</i> zone (about 40.0 m thick):	
Limestone, cream-colored, soft, chalky, rubbly-weathering, rarely calcarenitic.....	23.2
Shale, poorly exposed, olive-green; rare layers of ironstone and chalky limestone.....	12.0
Covered; calculated 4.8 m to top of Dhibi limestone.....	about 4.8

SECTION 29.—*Khashm at Turab*—Continued

Lower Dhurma Formation (about 126.0 m thick):	Thickness (meters)
2. Post- <i>Dorastensis</i> beds (about 102.3 m thick):	
Covered.....	102.3
1. <i>Dorastensis</i> zone (23.7 m thick):	
Shale, poorly exposed, red and green, gypsiferous; occasional very thin beds of tan platy aphanitic limestone and calcarenite. Interval capped by 1.6-m-thick bed of dark-brown, fine- to medium-grained, tightly cemented sandstone.....	23.7
Approximate total thickness of Dhurma Formation.....	374.7

SECTION 30.—*Al Jurayfah*

[Generalized section of the Dhurma Formation near Al Jurayfah; measurements by R. A. Bramkamp, S. B. Henry, M. C. Coffield, S. J. Roach, and R. B. Carr, 1951, and A. F. Pocock and R. P. Kopp, 1948.]

Limestone of the Tuwaiq Mountain Limestone (Upper Jurassic).	Thickness (meters)
Upper Dhurma Formation (82.9 m thick):	
6. Hisyay and 'Atash Members (82.9 m thick):	
Shale, olive-tan, brown, pale red, commonly gypsiferous, rarely calcareous; common limonite oolites in lower part, rare thin beds of reddish-brown oolitic calcarenitic limestone and calcarenite in upper part..	82.9
Middle Dhurma Formation (about 147.8 m thick):	
5. <i>Dhurmaites</i> zone (47.2 m thick):	
Shale, olive-gray, calcareous, gypsiferous; several thin beds of brown, ferruginous, ripple-marked sandstone near top.....	25.7
Covered; probably gypsiferous shale; single 0.9-m-thick bed of brown well-sorted medium-grained sandstone exposed near middle.....	21.5
4. <i>Micromphalites</i> zone (29.2 m thick):	
Shale, dominantly olive-gray and yellow-green, gypsiferous; occasional thin beds of buff platy limestone in lower part and tan well-cemented crossbedded sandstone in upper part.....	29.2
3. <i>Tulites</i> zone (36.4 m thick):	
Limestone, cream-colored to gray, soft, in part shelly and oolitic; 1.5-m-thick bed of tightly cemented calcarenite caps interval. About one-third of interval is covered, probably masks shale.....	20.0
Shale, poorly exposed, gray, tan, olive-green, gypsiferous; occasional very thin beds of light-tan limestone.....	16.4
2. <i>Thambites</i> zone (about 35.0 m thick):	
Shale, olive-green to tan, gypsiferous; occasional thin beds of tan soft impure limestone. Base of interval marks approximate equivalent to top of Dhibi limestone..	about 35.0
Lower Dhurma Formation (about 123 m thick):	
1. Pre- <i>Thambites</i> beds (about 123 m thick):	
Shale, poorly exposed, olive-gray, rarely calcareous; essentially equivalent to Dhibi limestone.....	13.9

SECTION 30.—*Al Jurayfah*—Continued

Lower Dhurma Formation (about 123 m thick)—Continued
Pre-*Thambites* beds (about 123 m thick)—Con.

Shale and sandstone; poorly exposed but dominantly red and tan shale with common interbedded yellow-brown to black, medium- to coarse-grained, in part calcareous, ferruginous sandstone; occasional thin beds of gray to tan, tightly cemented, shelly and oolitic calcarenite in upper part..... 55.1
Covered; interval calculated..... about 54.0

Approximate total thickness of Dhurma Formation..... 353.7
Marrat Formation.....

TUWAIQ MOUNTAIN LIMESTONE SECTIONS

SECTION 31.—*Riyadh water well 1*

(Tuwaiq Mountain Limestone reference section from Riyadh water well 1 (lat 24°38'42" N, long 46°49'22" E.) between depths 317.6 and 620.6 m. Detailed description and lithologic summary by N. M. Layne, Jr., and R. W. Fowers, 1957)

Impure limestone of the Hanifa Formation (Upper Jurassic).
Tuwaiq Mountain Limestone:
Aphanitic limestone, gray to tan, compact, slightly impure; thin bed of dark-gray, poorly sorted, skeletal calcarenite at base..... 4.9
Aphanitic limestone, light-tan, moderately porous; Foraminifera common, rare gray to white chert.. 24.4
Calcareous limestone, tan, moderately porous, skeletal; thin bed of gray-tan, strongly cemented, fine-grained, skeletal calcarenite at base..... 6.1
Aphanitic limestone, tan, slightly impure, moderately porous; common "birdseye" texture, rare white chert..... 9.1
Calcareous limestone, gray, partially recrystallized, fine-grained, pellet-skeletal..... 5.5
Aphanitic limestone and calcarenite; complexly interbedded tan compact aphanitic limestone and gray fine-grained well-cemented biogenic calcarenite; common chert..... 3.7
Aphanitic limestone, tan, compact; common "birdseye" texture..... 4.9
Calcareous limestone, dominantly tan, fine- to medium-grained, well-cemented, partially recrystallized, pellet-skeletal; common interbeds of tan aphanitic and calcarenitic limestone..... 13.4
Aphanitic limestone, tan compact, rarely pelleted; commonly mottled with "birdseye" texture; rare thin beds of tan, fine- to medium-grained calcarenitic limestone. Thin bed of gray, fine- to medium-grained, weakly cemented calcarenite at base..... 33.5
Aphanitic limestone, tan to gray, compact, in part marly and impure, rarely partially dolomitized; occasional thin beds of gray compact pellet calcarenitic limestone. Interval becomes progressively more marly, impure, and pelleted in the basal part..... 97.5

Total thickness of Tuwaiq Mountain Limestone..... 203.0
Limestone and subordinate shale of the Dhurma Formation.....

SECTION 32.—*Al Ghaf*

[Generalized section of Tuwaiq Mountain Limestone at Al Ghaf; measurements by S. S. Roach, 1962]

Dolomite of Hanifa Formation (Upper Jurassic).
Tuwaiq Mountain Limestone:
Limestone, cream-colored to tan, gray- and yellow-weathering, alternating hard and soft, finely granular, commonly elastic-textured and oolitic; abundant masses of chert in upper beds..... 7.6
Marl, tan, brown-weathering, soft, earthy, massive. 8.3
Shale, brown, fissile, calcareous..... 6.0
Limestone, cream-colored, yellow-weathering, calcarenitic; thin nodular bedding..... 10.0
Residual coral, colonial corals in matrix of soft aphanitic and calcarenitic limestone; forms distinctive brown-weathering band..... 8.3
Aphanitic limestone, light-gray to tan, compact, massive, chalky; abundant coral heads throughout. Lower 25.0 m forms vertical cliff. Thin 1.0-m-thick bed of tan coarse-grained oolitic calcarenite 20.0 m below top of interval is at top of first cliff of Tuwaiq escarpment..... 56.4
Calcareous limestone; dominantly tan coarse-grained, tightly cemented, in part oolitic calcarenite intimately interbedded with tan chalky aphanitic and calcarenitic limestone; forms band in cliff face..... 12.0
Aphanitic limestone, light-gray, soft, chalky, sparsely detrital; common thin beds of tan, tightly cemented calcarenite and calcarenitic limestone. Coral heads occur at several levels..... 23.2
Total thickness of Tuwaiq Mountain Limestone..... 131.8
Limestone and subordinate shale of the Dhurma Formation.....

SECTION 33.—*Khashm Fardah*

[Generalized section of Tuwaiq Mountain Limestone at Khashm Fardah; measurements by R. A. Brumkamp, B. Beverly, Jr., and S. B. Henry, 1964]

Dolomite of Hanifa Formation (Upper Jurassic).
Tuwaiq Mountain Limestone:
Dolomite and calcarenite; red, gray, and tan, medium-grained crystalline dolomite with abundant ghosts of branching stromatopora and head corals complexly interbedded with tan, strongly cemented, poorly sorted, fine-grained to gravel-sized, stromatopora-coral calcarenite; common interbeds of tan, partially dolomitized aphanitic and calcarenitic limestone..... 25.2
Aphanitic limestone, cream-colored to tan, poorly bedded, compact; forms vertical cliff with some irregular ledges. Common corals at several levels... 38.1
Sandstone, yellowish-tan, scoriaceous-weathering, well-cemented, massive..... 6.5

Total thickness of Tuwaiq Mountain Limestone... 69.8
Dhurma Formation.....

SECTION 34.—*Al 'Ārīd*

[Generalized section of the Tuwaiq Mountain Limestone at lat 18°22' N. (Al 'Ārīd escarpment); measurements by R. A. Brankamp, S. B. Henry, and G. W. Haksine, 1960]

	Thickness (meters)
Calcarenite of the Hanifa Formation (Upper Jurassic).	
Tuwaik Mountain Limestone:	
Calcarenite and limestone; dominantly tan to gray, tightly cemented, medium-grained to gravel-sized, stromatoporeid-coral-oolite calcarenite with common interbeds of cream-colored soft aphanitic and calcarenitic limestone; thin bed of red, finely crystalline dolomite is presently near base.....	32.4
Aphanitic limestone, cream-colored, soft, platy- and rubbly-weathering, in part poorly exposed, chalky; common thin beds of tan, tightly cemented, stromatoporeid-coral-oolite calcarenite throughout.....	15.1
Sandstone, brown to reddish-brown, well-cemented, medium-grained, calcareous; rare fossil casts.....	4.1
Limestone, cream-colored to gray, compact, chalky, aphanitic; alternating beds of sandstone in lower 3.3 m.....	6.9
Sandstone, brown, well-cemented, medium-grained.....	3.4

Total thickness of Tuwaiq Mountain Limestone.. 61.9
Sandstone of the Khuff Formation.

HANIFA FORMATION SECTIONS

SECTION 35.—*Jabal al Abakkayn*

[Hanifa Formation reference section was measured in a continuous traverse at Jabal al Abakkayn by R. W. Powers, L. F. Ramirez, and N. M. Layne, Jr., in 1960]

	Thickness (meters)
Limestone of the Jubaila Limestone (Upper Jurassic).	
Hanifa Formation:	
2. Calcarenite and calcarenitic limestone (18.9 m thick):	
Oolite calcarenite, yellow to reddish-brown, tightly cemented, in part sandy, slabby-weathering, coarse-grained; forms major bench.....	2.5
Poorly exposed; probably yellowish-cream, chalky, oolite calcarenitic limestone; forms scree-covered slope.....	4.8
Oolite calcarenitic limestone, dark-gray, hard, in part sandy, slabby to rubbly-weathering, partially dolomitized; interval capped by very thin bed of golden-brown oolite and calcarenite. Equivalent to top of Jabal al Abakkayn.....	1.9
Oolite calcarenite, yellowish-brown, well-cemented, sandy, medium-grained; abundant organic detritus on weathered surface.....	2.0
Sandstone, yellow, friable, calcareous, fine-grained, rubbly-weathering.....	1.6
Oolite calcarenite, golden-brown, well-cemented, medium- to coarse-grained, in part sandy; abundant fossil debris.....	1.1
Limestone, cream-colored, soft, chalky, in part finely oolitic.....	1.6
Poorly exposed; probably limestone as below grading upward into tan well-cemented medium-grained oolite; marked color change at base.....	3.4

SECTION 35.—*Jabal al Abakkayn*—Continued

	Thickness (meters)
Hanifa Formation—Continued	
1. Aphanitic limestone, calcarenitic limestone, and shale (94.4 m thick):	
Limestone, cream-colored to gray, soft, marly, in part finely oolitic; forms massive ledge.....	3.0
Limestone, poorly exposed, cream-colored, chalky, in part finely oolitic; forms scree slope with abundant fossils, becoming harder in upper part at base of prominent ledge.....	16.1
Limestone, gray to brown, chalky, rubbly-weathering, in part finely oolitic and poorly exposed; common very thin interbeds of golden-brown, tightly cemented, coarse-grained oolite calcarenite, abundant fossil fragments throughout. Rubbly-weathering scree slope covers lower part of interval.....	18.0
Shale, yellowish-gray to brick-red, chippy-weathering; several very thin layers of golden-brown, well-cemented, finely oolitic, slabby-weathering, partly sandy calcarenite.....	10.1
Limestone, cream-colored to reddish-brown, soft, chalky and marly, chippy- to rubbly-weathering, in part finely oolitic, fossiliferous; occasional thin beds of dark-golden-brown, tightly cemented calcarenite. Limestone becomes strongly coralliferous in lower part and cherty at base of interval.....	40.6
Shale, yellowish-tan, chippy-weathering, gypsiferous; interval poorly exposed but lithology verified by digging.....	6.6
Total thickness of the Hanifa Formation.....	113.3
Tuwaik Mountain Limestone.	

SECTION 36.—*Vicinity of Al Ghāf*

[Generalized section of the Hanifa Formation near Al Ghāf; measurements by S. J. Roach, 1962]

	Thickness (meters)
Dolomite of the Jubaila(?) Limestone (Upper Jurassic).	
Hanifa Formation:	
Limestone, tan, granular, chippy-weathering, in part calcarenitic; top of interval considered possible equivalent of Hanifa-Jubaila contact but dolomitization and lack of marker beds makes placement of Hanifa top uncertain in this area.....	3.3
Dolomite, light-tan, thin-nodular-bedded, finely crystalline; common relic clastic texture and thin interbeds of brown, tightly cemented calcarenite.....	9.0
Limestone, off-white to light-gray, abundantly coralliferous, nodular to indistinctly bedded, in large part calcarenitic; common thin interbeds of tan, tightly cemented oolite calcarenite.....	23.6
Calcarenite and limestone; dominantly tan, strongly cemented, coarse-grained, oolite calcarenite complexly interbedded with tan oolite calcarenitic limestone; some thin interbeds of tan aphanitic limestone; abundant coral heads throughout.....	18.8
Dolomite, brown, coarsely crystalline; capped with thin bed of chert.....	5.0
Approximate total thickness of Hanifa Formation.....	59.7
Tuwaik Mountain Limestone.	

SECTION 37.—*Khashm al Far' id*

[Generalized section of the Hanifa Formation near Khashm al Far' id; measurements by R. A. Brankamp, S. B. Henry, and G. W. Bhakale, 1949]

Limestone of the Jubaila Limestone (Upper Jurassic).

	Thickness (meters)
Hanifa Formation:	
Aphanitic limestone, poorly exposed, light-gray, soft, platy-weathering, compact, partially dolomitized; capped by 0.1-m-thick bed of tan, medium- to coarse-grained, tightly cemented, skeletal-oolite calcarenite.....	3.6
Dolomite, dark-gray, porous, finely crystalline.....	4.6
Covered; 1.0-m-thick bed of tan, coral-bearing, medium-grained, tightly cemented oolite calcarenite occurs near middle.....	13.5
Calcarenite and limestone; mainly gray-brown, medium- to coarse-grained, tightly cemented, coralliferous-stromatoporaoid-oolite calcarenite and coarse carbonate intimately interbedded with off-white, partially dolomitized aphanitic limestone.....	14.4
Covered.....	7.2
Oolite calcarenite, tan, tightly cemented, poorly sorted, abundantly coralliferous and stromatoporaoid, coarse-grained to conglomeratic.....	12.5
Calcarenite and limestone; dominantly tan, tightly cemented, medium-grained to gravel-sized, coralliferous-stromatoporaoid-oolite calcarenite; subordinate beds of cream-colored, soft, partially dolomitized aphanitic limestone.....	27.3

Total thickness of Hanifa Formation..... 83.1
Tuwaiq Mountain Limestone.

JUBAILA LIMESTONE SECTIONS

SECTION 38.—*Wadi Nisab*

[Jubaila Limestone reference section composed from three measured increments in Wadi Nisab. The lower part was described by E. L. Berg and R. L. Myers in 1946, the middle by R. A. Brankamp and S. B. Henry 1949, and the upper by R. W. Fowers and H. A. McClure in 1941]

Calcarenite of the Arab Formation (Upper Jurassic).

	Thickness (meters)
Jubaila Formation:	
4. Aphanitic and calcarenite limestone (6.0 m thick):	
Aphanitic limestone, tan to yellow, tight, chippy-weathering, partially recrystallized; single thin bed of gray, tight, skeletal calcarenite limestone near middle.....	1.5
Calcarenite limestone, tan to yellow, tight, chippy-weathering, skeletal; occasional thin layers of aphanitic limestone and beds of gray-brown, tightly cemented calcarenite near middle and at base.....	4.5
3. Calcarenite (7.0 m thick):	
Pellet-skeletal calcarenite, gray to golden-brown, tightly cemented, fine- to medium-grained, rarely sandy; thin bed of golden-brown, tightly cemented, partially dolomitized, coarse stromatoporaoid carbonate near base. Part of interval is poorly exposed.....	7.0
2. Calcarenitic limestone and calcarenite (20.5 m thick):	
Dolomite, dark-reddish-brown, compact, finely crystalline.....	1.0

SECTION 38.—*Wadi Nisab*—Continued

Jubaila Formation—Continued

2. Calcarenitic limestone and calcarenite (20.5 m thick)—Continued

	Thickness (meters)
Limestone and calcarenite; complexly interbedded, off-white to reddish-brown, partially dolomitized, tight, fine- to medium-grained, pellet-skeletal calcarenitic limestone and cream-colored to golden-brown, tightly cemented, partially recrystallized, fine- to medium-grained, pellet-skeletal calcarenite.....	12.5
Calcarenitic limestone, cream to yellow, tight, partially dolomitized, fine- to medium-grained, pellet-skeletal; rare thin beds of aphanitic limestone, common scattered coarse-grained shell debris at various levels.....	7.0
1. Aphanitic limestone (84.8 m thick):	
Aphanitic and calcarenite limestone, approximately equal amounts of complexly interbedded, cream-colored to yellow, tight, commonly partially dolomitized, very rarely sandy aphanitic limestone and golden-brown, tight, fine- to medium-grained, partially dolomitized, pellet-skeletal calcarenitic limestone; occasional thin beds of tan, tightly cemented calcarenite and finely crystalline dolomite.....	22.0
Aphanitic limestone, cream-colored to tan, chippy- to rubbly-weathering, tight, rarely chalky, commonly sandy; occasional thin beds of brown, pellet-skeletal calcarenitic limestone and tightly cemented calcarenite.....	62.8

Total thickness of Jubaila Limestone... 118.3
Hanifa Formation.

SECTION 39.—*Wadi Huraymil*

[Generalized section of the Jubaila Limestone at Wadi Huraymil; measurements by R. A. Brankamp and S. J. Roach, 1952]

Brecciated calcarenite of the Arab Formation (Upper Jurassic).

	Thickness (meters)
Jubaila Formation:	
Dolomite, poorly exposed, light-gray, finely crystalline; some partially dolomitized aphanitic limestone.....	3.7
Aphanitic limestone, light-gray, chippy-weathering, tight.....	4.5
Dolomite, dark-gray, massive, finely to medium-grained crystalline.....	10.0
Pellet-oolite calcarenite, cream-colored to yellow-orange, tightly cemented, medium- to coarse-grained shelly; common coral heads. Interval becomes aphanitic and sandy toward top. Forms conspicuous ledge.....	8.4
Dolomite, gray-brown, medium-grained crystalline; a few thin layers of aphanitic limestone.....	8.9
Aphanitic limestone, poorly exposed, cream-colored, soft, chalky; common thin interbeds of calcarenitic limestone and tightly cemented calcarenite.....	5.1
Sandstone, cream-colored, friable, fine-grained; some interbeds of tan, soft, sandy, aphanitic limestone.....	5.5

SECTION 39.—*Wadi Huraymila*—Continued

Jubbala Formation—Continued		Thickness (meters)
Aphanitic limestone, cream-colored, soft, rubbly to chippy-weathering, in part calcarenitic; occasional thin beds of brown, tightly cemented pellet-oolite calcarenite in upper part.....	28.1	
Total thickness of Jubbala Limestone.....	74.2	
Limestone of the Hanifa Formation.		

SECTION 40.—*Widiyan at Majama'*

[Generalized section of Jubbala Limestone along lat 28°2' N.; measurements by R. A. Brankamp, R. W. Powers, N. M. Layne, Jr., A. E. Clements, and F. R. Waldron, 1953]

Limestone of Arab Formation (Upper Jurassic).		Thickness (meters)
Jubbala Limestone:		
Dolomite, off-white to gray-brown, porous, in part poorly exposed, commonly ledge-forming, mostly medium-grained crystalline; capped by 2.0-m-thick bed of tan limestone that locally grades to black-weathering, strongly ferruginous, fine-grained sandstone. Dolomite includes a number of coral- and stromatopore-bearing biohermal layers.....	81.4	
Sandstone, tan to gray-tan, crossbedded, poorly sorted, friable, rarely conglomeratic; common fragments of indeterminate marine fossils.....	30.4	
Dolomite and limestone; poorly exposed but covered surface littered with red-brown dolomite and gray and yellow slabs of limestone.....	12.2	
Sandstone, tan, crossbedded, poorly sorted.....	4.4	
Limestone, tan, sandy; complexly interbedded with tan sandstone, yellowish-red dolomite, and brown sandy coquina.....	10.2	
Sandstone, brown, crossbedded, poorly sorted, in part conglomeratic; shell fragments common.....	12.4	
Total thickness of Jubbala Limestone.....	151.0	
Hanifa Formation.		

ARAB FORMATION SECTIONS

SECTION 41.—*Dammam well 7 and Abqaiq well 71*

[Arab Formation type-reference section from Dammam well 7 and Abqaiq well 71 respectively. R. A. Brankamp and H. A. Kimball in 1955 described the type section; R. W. Powers in 1960 designated the lowermost 5.0 m of Arab Formation from Abqaiq well 71 a reference section based on new D-Member carbonate data developed through thin-section analysis (Powers, 1962)]

Anhydrite of Hith Anhydrite (Upper Jurassic).		Thickness (meters)
Arab Formation:		
A Member (16.8 m thick):		
Aphanitic limestone, tan to brown.....	1.5	
No recovery.....	3.1	
Aphanitic limestone, tan to brown, tight.....	3.0	
Aphanitic limestone and calcarenite; complexly interbedded, tan, tight aphanitic limestone and brown, tightly cemented, medium-grained pellet calcarenite.....	9.2	
B Member (10.7 m thick):		
Anhydrite, white, massive; subordinate thin interbeds of tan, partially dolomitized, aphanitic limestone.....	4.6	
Aphanitic limestone, tan, tight; minor thin interbeds of brown, moderately cemented pellet calcarenite.....	4.6	

SECTION 41.—*Dammam well 7 and Abqaiq well 71*—Continued

Arab Formation—Continued		Thickness (meters)
B Member (10.7 m thick)—Continued		
Dolomite, brown, finely crystalline; relic clastic texture.....	1.5	
C Member (41.5 m thick):		
Anhydrite, off-white to gray, rarely brown, massive.....	12.1	
Aphanitic limestone, brown, moderately porous, impure; rare irregular blebs of anhydrite.....	0.1	
Anhydrite, off-white, massive.....	0.6	
Aphanitic limestone, tan, porous, chalky partially dolomitized; some intergrown brown coarse anhydrite crystals.....	1.3	
Dolomite, tan to light-brown, porous, finely crystalline; relic clastic texture.....	0.1	
Calcarenite, light-brown, moderately cemented, partially recrystallized, fine-grained.....	2.2	
Calcarenite limestone, light-brown, moderately porous.....	0.4	
Calcarenite, tan, partially recrystallized, strongly cemented, fine-grained; abundant intergrown brown anhydrite in lower part.....	0.5	
Aphanitic limestone, light-brown, compact, partially dolomitized.....	0.3	
Calcarenite, brown, partially recrystallized and dolomitized, fine-grained, moderately porous, pellet.....	0.2	
Aphanitic limestone, brown, tight.....	0.2	
Calcarenite, tan, moderately cemented, partially recrystallized, fine-grained.....	0.1	
Aphanitic limestone, light-brown, moderately porous to tight; thin interbeds of brown, moderately cemented calcarenite.....	2.0	
Calcarenite, light-brown, weakly to tightly cemented, partially recrystallized, fine-grained, commonly foraminiferal.....	8.1	
Aphanitic limestone, gray-brown, tight, lithographic.....	0.2	
Calcarenite, tan, porous, partially recrystallized, fine-grained.....	0.3	
Aphanitic limestone, brown, tight, stylolitic.....	0.1	
Calcarenite, light-brown, moderately to tightly cemented, fine- to medium-grained, partially recrystallized; rare blebs of anhydrite in upper part and some coarse fragments of older limestone in lower.....	2.0	
Calcarenitic limestone, brown, porous; grains set in lime-mud matrix.....	0.1	
Calcarenite, brown, moderately porous; common clear calcite cement.....	0.3	
Calcarenitic limestone, brown, moderately porous, pellet-detrital.....	0.1	
Calcarenite, tan to brown, porous to moderately cemented, in part partially recrystallized, fine- to medium-grained; small high-spired gastropods and indeterminate molluscs rather common.....	9.0	
Dolomite, brown, medium-grained, crystalline; relic calcarenite texture often with voids in place of grains. Ghosts of stromatopore fragments.....	1.2	

SECTION 41.—Dammam well 7 and Abqaiq well 71—Continued

Arab Formation—Continued

D Member (55.0 m thick):

	Thickness (meters)
Anhydrite, off-white, massive; rare, very thin laminations of brown dolomite and gray aphanitic limestone.....	1.5
Dolomite, brown, porous, finely crystalline; relic elastic texture and common blebs of brown and off-white anhydrite.....	0.8
Anhydrite, off-white, massive; rare laminations of brown limestone and dolomite.....	2.0
Calcarenite, gray-brown, strongly cemented, tight, fine-grained; common crystals of authigenic anhydrite.....	0.5
Dolomite, brown, porous, finely crystalline; relic elastic texture.....	0.7
Anhydrite and dolomite; approximately equal amounts, completely interbedded mottled white and brown anhydrite and dolomite.....	0.5
Anhydrite, white to pale-gray, massive; occasional irregular stringers of dark-brown limestone.	6.5
Aphanitic limestone, gray, compact; some disseminated pyrite.....	0.1
Dolomite, tan, porous, finely crystalline; relic elastic texture and some irregular laminations of white and brown anhydrite.....	0.8
Calcarenite, tan, moderately porous, strongly recrystallized, fine-grained; voids and ghosts in place of elastic grains.....	0.3
Anhydrite, white to pale-gray, massive; rare streaks of aphanitic limestone and dolomite.....	0.6
Anhydrite and calcarenite; completely interbedded white anhydrite and tan, moderately porous, strongly recrystallized calcarenite with relic elastic texture.....	0.7
Calcarenite, tan, moderately porous, fine-grained, strongly recrystallized; grains are commonly voided.....	0.4
Anhydrite, white to pale-gray, massive.....	2.6
Calcarenitic limestone, light-brown, moderately porous, poorly sorted, fine- to medium-grained, partially dolomitized, aggregate pellet; core of pellets commonly voided and filled with chert (variety microcrystalline quartz) and authigenic anhydrite. Some algal debris. Pore space consists of highly tortuous channels and unfilled voids in pellets. Rare Foraminifera.	0.2
Calcarenitic limestone, brown, tight, poorly sorted, fine- to medium-grained, dominantly aggregate pellet; very small patches of pellets show void porosity and anhydrite filling as above. Rare isolated coarse crystals of authigenic anhydrite. Foraminifera common.....	0.4
Calcarenite, brown, tight to moderately porous, poorly sorted, medium- to coarse-grained, angular- to well-rounded, pellet-algal; more than 30 percent algal debris, mostly dasyclad forms. About 30 percent coarsely crystalline authigenic anhydrite. Foraminifera common.	0.3
Coarse carbonate, brown, tightly cemented, "algal" nodule; dominantly gravel-sized aggregates of fine particles with well-developed concentric layering.....	0.3

SECTION 41.—Dammam well 7 and Abqaiq well 71—Continued

Arab Formation—Continued

D Member (55.0 m thick)—Continued

	Thickness (meters)
Calcarenitic limestone, dark-brown, tight, well-sorted, partially dolomitized and recrystallized; 10 percent fine-grained, well-rounded aggregate pellets. Dolomite, mosaic calcite, and coarse authigenic anhydrite scattered uniformly through rock.....	0.2
Coarse carbonate, brown, moderately porous, partially recrystallized, gravel-sized, "algal" nodule; nodules are composed of lime mud and sand-sized grains of algal trash and pellets, concentric layering is well developed. Many grains surrounded by a thin crust of needlelike calcite crystals growing normal to the grain surface (drusy coat).....	0.1
Calcarenite, brown, tight, poorly sorted, fine- to medium-grained, in part strongly recrystallized and partially dolomitized, algal debris-aggregate pellet; large patches have been recrystallized to very finely crystalline calcite mosaic and original texture is obscure.....	0.3
Calcarenitic limestone, light-gray-brown, tight, fine- to medium-grained, partially dolomitized and partially recrystallized, algal; rare Foraminifera.....	0.2
Calcarenite, lithology as in 0.3-m-thick calcarenite above.....	0.1
Calcarenitic limestone, light-gray-brown, moderately porous, moderately sorted, partially dolomitized, fecal pellet; pellets are fine to medium grained, oval shaped, and set in lime-mud matrix. Irregular flattening suggests pellets soft at time of deposition. Some algal debris and crystals of authigenic anhydrite in lower part; very rare Foraminifera.	0.7
Aphanitic limestone, brown, tight, partially dolomitized; a few scattered fine-grained aggregate pellets and fecal pellets.....	0.2
Dolomite, dark-brown, tight, euhedral to partly anhedral, finely crystalline; medium to coarsely crystalline anhydrite is intimately intergrown.....	0.3
Calcarenite, brown, moderately porous, well-sorted, medium-grained, heterogeneous but dominantly algal debris; 10 to 15 percent aggregate pellets and ooliths. Drusy coating is well developed around individual grains. Interval strongly recrystallized with dolomite and large calcite crystals concentrated in algal debris which is more susceptible to alteration than other particle types. Very rare Foraminifera.....	0.1
Calcarenitic limestone, brown, tight, moderately sorted, dominantly fine- to medium-grained, angular to well-rounded, heterogeneous but mostly aggregate pellet-algal; some partially dolomitized, oolitic calcarenitic limestone in middle part. Much of original mud matrix appears to be algal dust highly susceptible to recrystallization. Foraminifera very common.....	1.2

SECTION 41.—Dammam well 7 and Abqaiq well 71—Continued

Arab Formation—Continued

D Member (55.0 m thick)—Continued

Thickness
(meters)

Calcarenite, gray-brown, moderately porous, well-sorted, medium- to coarse-grained, well-rounded, aggregate pellet; some algal debris. All grains surrounded by well-developed drusy coat of acicular calcite crystals. Some clear calcite cement and coarse crystals of authigenic anhydrite. Rare Foraminifera.....	0.6
Calcarenitic limestone, dark-red-brown, moderately porous, moderately sorted, fine- to medium-grained, aggregate pellet calcarenitic limestone and poorly sorted stromatoporeid, coarse calcarenitic limestone; 10 percent algal debris, rare Foraminifera. Original mud matrix discontinuous and makes up 20 percent of rock. Some authigenic anhydrite crystals.	0.5
Aphanitic limestone, brown, tight, partially dolomitized; 25 percent uniformly scattered, finely crystalline euhedral dolomite. Rare Foraminifera.....	2.0
Calcarenitic limestone, brown, tight, well-sorted, well-rounded, aggregate pellet; 50 percent finely crystalline dolomite rhombs and 20 percent medium-grained aggregate pellets in original lime-mud matrix. Very rare Foraminifera.....	0.4
Aphanitic limestone, brown, tight, partially dolomitized.....	0.3
Dolomite, brown, finely crystalline; well-developed intercrystalline porosity. Thin bed near top contains about 30 percent chert cement (variety microcrystalline quartz) and some authigenic anhydrite that effectively plug intercrystalline pore space. Dolomite crystals vary in size from 0.06 to 0.15 mm....	3.1
Aphanitic limestone, brown, tight, partially dolomitized.....	0.2
Calcarenitic limestone, light- to dark-brown, heterogeneous, poorly sorted, fine- to coarse-grained, angular to well-rounded, moderately porous, aggregate pellet-algal-stromatoporeid; pore shape highly irregular owing to odd particle shape and common disruption of mud matrix. Rare Foraminifera.....	3.0
Coarse carbonate, brown, moderately porous, poorly sorted, medium-grained to gravel-sized, aggregate pellet-algal-"algal" nodule; rare Foraminifera. Bed is moderately well cemented with medium-grained crystalline, clear calcite.....	0.2
Calcarenitic limestone, dark-brown, moderately porous, "algal" nodule; rare Foraminifera.....	0.2
Coarse carbonate, dark-brown, moderately porous to tight, poorly sorted, medium-grained to gravel-sized, angular to well-rounded, stromatoporeid-algal-"algal" nodule; significant amounts of aggregate pellets, Foraminifera common. "Algal" nodules commonly composed of 3- to 10-mm fragments of stromatoporeid encased in concentric layers of lime mud.....	0.7

SECTION 41.—Dammam well 7 and Abqaiq well 71—Continued

Arab Formation—Continued

D Member (55.0 m thick)—Continued

Thickness
(meters)

Calcarenitic limestone, gray to dark-brown, moderately porous to tight, poorly sorted, grains dominantly coarse-grained to gravel-sized, angular to well-rounded "algal" nodule-algal-aggregate pellet; rare Foraminifera and stromatoporeid fragments. Percentage of different types of sand- and gravel-sized grains quite variable but mud matrix usually forms 50 percent or more of rock throughout interval. Pore space most commonly of disrupted or solution channel type. Channels partly filled with clear calcite cement.....	3.1
Coarse carbonate, dark-brown, slightly porous, poorly sorted, medium-grained to dominantly gravel-sized, angular to well-rounded, heterogeneous, "algal" nodule; 10 to 15 percent each of aggregate pellets, stromatoporeid fragments, and algal debris, rare Foraminifera. About 5 percent mud-sized grains trapped between larger elastic particles tends to seal porosity....	0.2
Calcarenitic limestone, dark-brown, poorly sorted, medium-grained to gravel-sized, strongly disrupted and channelled, aggregate pellet; 10 percent algal debris and 15 percent "algal" nodules; Foraminifera common.....	0.2
Calcarenitic, dark-brown, poorly sorted, fine-grained to gravel-sized, angular to well-rounded, moderately porous, aggregate pellet-algal; 20 percent "algal" nodules, Foraminifera common.....	0.2
Calcarenitic limestone, gray-brown, moderately porous, poorly sorted, fine-grained to gravel-sized, subangular to well-rounded, aggregate pellet; 20 percent stromatoporeid fragments and "algal" nodules occur at several levels; rare Foraminifera. Some channel porosity and calcite cement filling intragranular pore space within individual calcareous algae and stromatoporeid grains.....	0.9
Calcarenitic, brown, moderately to very porous, poorly sorted, fine-grained to gravel-sized, algal; about 20 percent each of stromatoporeid fragments and aggregate pellets, very rare Foraminifera. Pore shape highly irregular and often channelled wider than original packing size between grains.....	0.5
Calcarenitic limestone, medium-brown, porous, poorly sorted, medium-grained to gravel-sized stromatoporeid-aggregate pellet-"algal" nodule-algal; nearly equal amounts of the four main grain types are set in 15 percent original mud matrix, rare Foraminifera. Porosity is highly irregular and involves intragranular as well as channel type.....	0.6
Calcarenitic, dark-brown, very porous (20 percent visual), well-sorted, dominantly medium-grained, well-rounded, moderately cemented, aggregate pellet; Foraminifera common.....	0.3

SECTION 41.—*Dammam well 7 and Abqaiq well 71*—Continued

Arab Formation—Continued

D Member (55.0 m thick)—Continued

	Thickness (meters)
Aphanitic limestone, brown, partially dolomitized; some channel porosity filled with clear crystalline calcite, some stylolites, rare Foraminifera.....	0.6
Calcareenite, dark-brown, tight, moderately to strongly cemented, moderately sorted, medium- to coarse-grained, aggregate pellet; most pore space filled with clear, coarsely crystalline calcite cement (about 30 percent). Middle part strongly altered to deeply sutured mosaic of aggregate pellets in stylolitic contact with adjoining pellets. Significant amounts of algal debris and selective recrystallization of algal fragments and stromatoporeid grains in lower part. Foraminifera common.....	1.2
Coarse carbonate, light-gray-brown, low porosity, moderately cemented (about 10 percent), poorly sorted, medium-grained to gravel-sized, "algal" nodule; each grain surrounded by drusy coat of acicular calcite crystals generally followed by calcite cement. Many individual particles strongly recrystallized to mosaic calcite. Rare Foraminifera.....	0.2
Calcareenite, dark-brown, very low porosity, well-sorted and rounded, medium-grained, strongly cemented (about 25 percent), aggregate pellet; about 10 percent medium-grained, well-rounded fragments of stromatoporeid; Foraminifera common.....	0.5
Calcareenite, brown, porous, well-sorted, medium- to coarse-grained, aggregate pellet; common drusy coat around individual grains. Some stromatoporeid fragments, algal debris, and clear calcite cement, Foraminifera very common.....	1.6
Coarse carbonate, light-gray-brown, very porous, poorly sorted, dominantly gravel-sized, stromatoporeid-"algal" nodule; small patches of aggregate pellets and algal debris, small amount of mud matrix, rare Foraminifera. Pore shape is highly irregular and in part solution channel.....	0.4
Calcareenite limestone, dark-brown, porous, poorly sorted, fine-grained to gravel-sized, dominantly aggregate pellet; common "algal" nodules and algal debris, some molluscan fragments and Foraminifera common. From 20 to 50 percent original mud matrix.....	0.4
Coarse carbonate, brown, very porous, gravel-sized, skeletal.....	0.2
Calcareenite limestone, light-brown, porous, poorly sorted, medium- to coarse-grained, aggregate pellet; Foraminifera common.....	0.3
Calcareenite, light-brown, porous, well-sorted, medium- to coarse-grained, rarely angular to very well-rounded, aggregate pellet; 10 to 20 percent each of algal debris, Foraminifera, and "algal" nodules, rare stromatoporeid fragments.....	0.5

SECTION 41.—*Dammam well 7 and Abqaiq well 71*

Arab Formation—Continued

D Member (55.0 m thick)—Continued

	Thickness (meters)
Calcareenite limestone, light- to dark-brown, moderately to very porous, poorly sorted, rounded to angular, partially dolomitized, dominantly aggregate pellet; abundant stromatoporeid fragments, "algal" nodules, and algal debris at several levels, very rare Foraminifera. Common channel porosity, some intergranular pore shape very irregular.....	1.6
Coarse carbonate, light-gray, very porous (intergranular), gravel-sized, stromatoporeid; about 5 percent well-rounded aggregate pellets. Very rare Foraminifera.....	0.1
Calcareenite, light-brown, highly porous, moderately sorted, medium-grained to gravel-sized, well-rounded aggregate pellet; well-developed drusy coat around each grain, rare Foraminifera.....	0.2
Calcareenite limestone, dark-brown, highly porous, moderately sorted, dominantly fine to medium-grained, aggregate pellet; 10 percent algal debris, rare Foraminifera. "Fecal" pellets occur in lower part. Irregular shape of algal debris plus some channeling makes pore shape highly irregular.....	0.9
Calcareenite, brown, very porous, well-sorted and rounded, medium- to coarse-grained, weakly cemented, aggregate pellet; rare Foraminifera.....	0.2
Coarse carbonate, gray-brown, very porous, weakly cemented, moderately sorted, coarse-grained to gravel-sized, algal-aggregate pellet; individual grains covered by well-developed drusy coat. Rare Foraminifera.....	0.2
Calcareenite limestone, brown, tight, partially dolomitized, moderately sorted, dominantly fine to medium-grained, aggregate pellet; some algal debris near top, rare stromatoporeid, Foraminifera, and echinoderm fragments throughout.....	4.0
Dolomite, light-brown, tight to porous, open euhedral to strongly sutured anhedral mosaic, finely crystalline, (average crystal size about 0.12 mm); 10 percent chert (variety microcrystalline quartz) and authigenic anhydrite in upper part.....	1.0
Calcareenite dolomite, dark-brown, finely crystalline, tightly sutured; small percentage aggregate pellets, stromatoporeid fragments, and brachiopod debris as well as mud matrix visible in patches, trace authigenic anhydrite.....	0.1
Calcareenite limestone, light-gray-brown, moderately porous, tight, poorly sorted, fine-grained to gravel-sized, commonly disrupted, angular to well-rounded, partially dolomitized aggregate pellets; significant amounts of algal debris, "algal" nodules, and echinoid fragments occur at various levels, very rare Foraminifera.....	0.5

SECTION 41.—*Dammam well 7 and Abaqi well 71*—Continued

Arab Formation—Continued

D Member (55.0 m thick)—Continued

Calcareneite, light-brown, compact, moderately sorted, angular to well-rounded, aggregate pellet; pore space is intergranular and clean; however, many grains appear to have been soft on deposition and later compacted and distorted. Rare Foraminifera.....

Thickness
(meters)

0.5

Total thickness of Arab Formation..... 124.0

Jubaila Limestone.

SECTION 42.—*Wadi Nisab*

[Generalized section of the basal Arab Formation at Wadi Nisab; measurements by R. W. Powers and H. A. McClure in 1961]

Carbonate of the middle and upper Arab Formation (Upper Jurassic).

Basal Arab carbonate:

Calcareneite, gray, tightly cemented, fine- to medium-grained, pellet-skeletal; thin bed of gray, tight, aphanitic limestone near middle.....

Thickness
(meters)

3.5

Solution-collapse breccia, gray-brown, coarse limestone breccia; fragments up to 1.0 m in diameter, usually angular, set in heterogeneous matrix of jumbled carbonate fragments.....

12.0

Sandstone, yellow, fine-grained, moderately cemented, calcareous, rounded to subrounded, quartzose.....

1.5

Aphanitic and calcareneite limestone, alternating layers of tan, tight, aphanitic limestone with rare blebs of anhydrite and reddish-brown, tight, pellet-skeletal calcareneite limestone.....

3.5

Calcareneite, yellow-brown, tightly cemented, fine- to medium-grained, sandy, pellet-skeletal.....

1.5

Total thickness of basal Arab carbonate unit..... 22.0

Jubaila Limestone.

HITH ANHYDRITE SECTION

SECTION 43.—*Daht Hii*

[Hith Anhydrite section at Daht Hii was first described and recognized as the type sequence by R. A. Brankamp and T. C. Burger in 1938. A detailed remeasurement by S. J. Roach in 1962 is given as follows]

Oolite (Upper Jurassic?) of Sulaiy Formation.

Disconformity.

Hith Anhydrite:

Limestone breccia, gray-tan, thin to platy, angular blocks recemented in fine-grained marl matrix; thin bed of gray-tan aphanitic and calcareneite limestone occurs in lower part. May represent slumped Sulaiy beds rather than residuum of Hith carbonates but interval originally contained at least one bed of anhydrite.....

Thickness
(meters)

12.7

Anhydrite, blue-gray, thin, regularly bedded, common color banding and lamination; some laminae of yellow clay shale in upper part. Highly irregular sinuous contact at top with thin beds of anhydrite clearly truncated; knobs and sharp pinnacles of anhydrite extend up to 0.5 m into the overlying breccia.....

32.0

Anhydrite, blue-gray, massive, finely nodular; few irregular lenses of white gypsum.....

2.0

SECTION 43.—*Daht Hii*—Continued

Hith Anhydrite—Continued

Thickness
(meters)

Anhydrite, massive; contains alternating bands of blue and white color.....

9.5

Anhydrite, blue-gray, massive; finely nodular partings.....

12.0

Anhydrite, blue-gray; some small nodules in a matrix of yellow-weathering argillaceous dolomite.....

2.1

Anhydrite, blue-gray, massive, laminated to platy; common sinuous partings and blue and white laminations and banding. Wavy flow structure prominent in parts of interval.....

20.0

Total thickness of Hith Anhydrite..... 90.3

Arab Formation.

SULAIY FORMATION SECTIONS

SECTION 44.—*Daht Hii*

[Sulaiy Formation exposed in Daht Hii; cliff above and back slope were studied and designated Sulaiy type section by R. A. Brankamp and T. C. Burger in 1938. The same outcrop, reworked in more detail by S. J. Roach in 1962, is given as follows]

Calcareneite of the Yamama Formation (Lower Cretaceous).

Sulaiy Formation:

Thickness
(meters)

Aphanitic limestone, off-white to tan to gray, thinly bedded, commonly nodular-weathering, rarely sandy; common thin interbeds of pellet-skeletal calcareneite limestone and tightly cemented calcareneite.....

14.3

Aphanitic limestone, light-gray, cream-colored-weathering, thinly bedded, moderately porous.....

7.0

Aphanitic limestone, light-gray, cream-colored-weathering, thinly and nodular-bedded, moderately porous; occasional thin interbeds of yellow-tan, pellet-skeletal calcareneite limestone and calcareneite.....

40.0

Aphanitic limestone, light-gray, cream-colored-weathering, thinly bedded, tight to moderately porous; a few thin beds of yellow-tan, pellet-skeletal calcareneite limestone and calcareneite. Top of interval caps escarpment above Daht Hii.....

44.5

Calcareneite limestone, tan to brown, rarely sandy, pellet-skeletal; some interbeds of aphanitic limestone and skeletal calcareneite.....

20.0

Aphanitic limestone, tan, thinly bedded, nodular, moderately porous; rare shell fragments.....

5.1

Calcareneite, tan, thinly bedded and nodular, tightly cemented, pellet-skeletal; at places grades to coquina-like calcareneite with pellet matrix. Small pebbles of older limestone are common in calcareneite beds. A few thin interbeds of tan, moderately porous aphanitic limestone.....

12.6

Aphanitic limestone, gray, tan-weathering, tight to moderately porous, thinly bedded and nodular; rare thin interbeds of calcareneite limestone. All beds are about 0.1 m thick and separated by well-defined bedding planes.....

14.7

Calcareneite, tan, tightly cemented, irregularly bedded, pellet-skeletal.....

12.0

Total thickness of Sulaiy Formation..... 170.2

Hith Anhydrite.

SECTION 45.—Near lat 25°50' N.

[Generalised section of Sulali Formation near latitude 25°50' N., measurements by R. W. Powers and H. A. McClure, 1962]

Calcarene of Yamama Formation (Lower Cretaceous).

	Thickness (meters)
Sulali Formation:	
Aphanitic limestone, golden-brown, tight, partially dolomitized.....	2.0
Pellet calcarenite, golden-brown, moderately sorted, medium- to coarse-grained, tightly cemented; abundant Foraminifera and pelecypod debris.....	1.8
Calcarene limestone, light-brown, moderately porous, chalky; 20 percent coarse-grained pelecypod and gastropod shell debris. Original shell material altered to clear, coarsely crystalline calcite. Lower 1.0-m-thick bed is tan aphanitic limestone.....	3.2
Pellet calcarenite, tan, fine-grained, well-sorted, tightly cemented; abundant Foraminifera.....	2.0
Aphanitic limestone, tan, moderately porous, chalky; very rare thin beds of brown, moderately porous, chalky pelecypod calcarenite limestone.....	35.5
Covered interval; thickness unknown.....	?
Aphanitic limestone, tan, moderately porous, chalky; thin beds of tan chalky, medium- to coarse-grained, pellet- molluscan calcarenite limestone occur near top.....	5.1
Pellet calcarenite, dark-brown, well-sorted, fine- to medium-grained, tightly cemented; thin bed of tan chalky aphanitic limestone occurs in upper part.....	4.0
Aphanitic limestone, tan, moderately porous, rarely pelletal; common outlines of monaxon sponge spicules. A 2.0-m-thick bed of brown, rarely sandy, chalky, pellet calcarenite limestone occurs near middle.....	5.5
Pellet calcarenite, golden-brown, well-sorted, very fine grained, tightly cemented.....	1.5
Aphanitic limestone, tan, moderately porous, chalky; rare scattered molluscan debris and some sponge spicules. Occasional thin beds of brown tight, fine- to medium-grained, pellet calcarenite limestone.....	14.5
Base of section probably near slump contact of Arab and Sulali Formations.	

YAMAMA FORMATION SECTION

SECTION 46.—Vicinity of lat 24°01' N.

[Yamama Formation reference section was measured and sampled in detail by H. W. Powers and H. A. McClure in 1962 near vicinity of type section about 20 km south of Al Yamamah (see pl. 17)]

Calcarene of the Buwaib Formation (Lower Cretaceous).

Unconformity.

	Thickness (meters)
Yamama Formation:	
3. Calcarene and aphanitic limestone (16.0 m thick):	
Pellet calcarenite, golden-brown, well-sorted, fine-grained, sparsely sandy.....	3.0
Covered; rare exposures of off-white, chalky, aphanitic limestone; upper 0.5 m forms cap of off-white nodular limestone.....	3.4
Aphanitic limestone, light-brown, tight; 5 percent sponge spicules. Oyster bed 1.1 m below top.....	1.6

SECTION 46.—Vicinity of lat 24°01' N.—Continued

Yamama Formation:—Continued

3. Calcarene and aphanitic limestone (16.0 m thick)—Continued

	Thickness (meters)
Pellet-foraminifera calcarenite, brown, moderately well sorted, tightly cemented; 20 percent tabular disarticulated pelecypod valves showing strong lineation parallel to bedding and set in matrix of medium- to coarse-grained pellets and Foraminifera all tightly cemented with clear secondary calcite. Hill-capping unit.....	0.4
Calcareous sandstone, golden-brown, tight, quartzose; 50 percent fine- to medium-grained, subrounded to angular quartz sand uniformly admixed with lime-mud matrix.....	0.6
Covered.....	1.0
Pellet calcarenite, golden-brown, well-sorted, fine-grained, rounded, tightly cemented; abundant calcite-replaced monaxon sponge spicules and scattered pelecypod debris.....	1.5
Covered.....	2.0
Pellet calcarenite, golden-brown, moderately well sorted, medium- to coarse-grained, tightly cemented, clean-washed; 5 percent coarse pelecypod debris and Foraminifera commonly scattered through the pellet calcarenite matrix.....	2.0
Pellet calcarenite, dark-golden-brown, well-sorted, very fine grained, tightly cemented; calcarenite so uniformly sorted and tightly cemented that on outcrop appears as aphanitic limestone with well-developed conchoidal fracture. Rare chert nodules. Extensive bench former; bed caps all hills in the area.....	0.5
2. Aphanitic and calcarenite limestone (10.1 m thick):	
Aphanitic limestone, tan, moderately porous, chalky, slightly sandy.....	1.5
Coarse pelecypod calcarenite limestone, tan to medium-brown, tight, poorly sorted; 50 percent disarticulated pelecypod valves, Foraminifera and pellets in a light-cream-colored, lime-mud matrix. Isolated pockets of clean, current-washed, tightly cemented Foraminifera-pellet calcarenite. Pelecypod debris replaced by clear crystalline calcite. Echinoids rather common.....	1.0
Aphanitic limestone, light-tan, moderately porous, chalky.....	0.7
Foraminifera-pellet calcarenite, golden-brown, tightly cemented, well-sorted; 5 percent recrystallized pelecypod shells.....	0.5
Aphanitic limestone, light-tan, moderately porous, sparsely sandy; abundant monaxon (?) sponge spicules scattered throughout; very rare molluscan debris.....	1.3

SECTION 46.—Vicinity of lat 24°01' N.—Continued

Yamama Formation—Continued

2. Aphanitic and calcarenitic limestone (10.1 m thick)—Continued

	Thickness (meters)
Calcarenites and limestone; tan, strongly cemented, well-sorted pellet calcarenite intimately interbedded with coarse molluscan calcarenitic limestone as below. Gastropods and Foraminifera uniformly scattered through both rock types. Weathered bench surface contains abundant, well-preserved pelecypods, echinoids, and scarce ammonites. <i>Pygurus cf. P. rostratus</i> common.....	0.5
Coarse molluscan calcarenitic limestone, brown, tight, poorly sorted; 60 percent calcite-replaced, gravel-sized pelecypod and gastropod shells randomly oriented in lime-mud matrix and commonly infilled with lime mud. Forms brown, biogenic limestone bench....	2.5
Partly covered; probably off-white, soft, chalky, aphanitic limestone.....	2.1
1. Calcarenites and coarse carbonate (19.4 m thick): Pellet-molluscan calcarenite, golden-brown, moderately well sorted, fine-grained, strongly laminated, tightly cemented; disarticulated pelecypod valves show definite lamination parallel to laminations. Foraminifera and gastropod debris common. Very thin bed of pelecypod calcarenitic limestone near top. Upper 0.3-m-thick bed forms prominent dip slope.....	3.3
Coarse gastropod carbonate, brown, poorly sorted, moderately cemented; 60 percent gastropod remains commonly infilled with cream-colored lime mud. Some gravel-sized fragments of tan aphanitic limestone apparently derived from older limestones. About 20 percent fine- to medium-grained Foraminifera.....	1.6
Pellet calcarenite, golden- to reddish-brown, generally well-sorted, tightly cemented, very fine to medium-grained; Foraminifera and molluscan debris common. Occasional thin beds of brown, poorly sorted, tightly cemented, coarse-grained to gravel-sized, coarse gastropod carbonate. Single 0.3-m-thick bed of golden-tan, tight aphanitic limestone 2.7–3.0 m below top of interval.....	9.5
Covered.....	1.0
Pellet calcarenite, as below, top of unit forms extensive dip slope.....	1.5
Covered.....	1.0
Pellet calcarenite, brown, poorly sorted, tightly cemented; poorly preserved arenaceous Foraminifera common. About 20 percent of debris is of organic origin, dominantly molluscan.....	1.5

Total thickness of Yamama Formation... 45.5

Sulayy Formation.

BUWAIB FORMATION SECTIONS

SECTION 47.—Near Khafs Daghrah

[Buwaib Formation reference section was measured and sampled in 1962 in detail by R. W. Powers and H. A. McClure 14 km northeast of Khafs Daghrah in vicinity of lat 24°34' N.]

Sandstone of the Biyadh Sandstone Lower (Cretaceous)

	Thickness (meters)
Buwaib Formation:	
Coarse pelecypod carbonate, golden-brown, gravel-sized, poorly sorted, sandy; almost exclusively pelecypod hash. Most pelecypod shells leached or replaced by clear crystalline calcite, rare original shell material. Angular to subrounded medium-grained quartz sand common.....	0.1
Dolomite, reddish-brown, rarely sandy, medium-grained crystalline; abundant ghosts of calcite-replaced pelecypod shells.....	1.9
Coarse pelecypod carbonate, reddish-brown, poorly sorted, strongly recrystallized and partially dolomitized; original texture partially obliterated by recrystallization; however, still possible to recognize original textural elements including pelecypod shells, pellets, and secondary calcite cement.....	0.2
Pellet calcarenite, golden-brown, moderately cemented very commonly sandy, well-sorted, fine- to medium-grained.....	0.6
Aphanitic limestone, brown, tight, partially recrystallized; forms soft rubbly bench.....	1.0
Coarse pelecypod carbonate, golden-brown, dominantly gravel-sized, moderately cemented; pelecypod shells replaced by coarsely crystalline calcite or leached; remaining internal molds of lime mud are most common gravel-sized grain.....	0.2
Poorly exposed; probably olive-green shale and impure aphanitic limestone; 0.1-m-thick beds of brown, rarely sandy, tightly cemented pellet calcarenite, form weak benches 2.0, 4.0, and 4.4 m above base of interval.....	6.3
Sandstone, dark-brown, strongly weathered, quartzose.....	1.0
Molluscan-foraminiferal calcarenite, golden-brown, poorly sorted, tightly cemented, partially recrystallized; large amounts of indeterminate molluscan? shell debris, Foraminifera, and pellets.....	1.5
Dolomite, reddish-brown, medium-grained crystalline, moderately porous; 10 percent original calcite matrix preserved in intercrystalline areas.....	1.5
Pellet calcarenite, golden-brown, very fine grained, angular to well-rounded, tightly cemented, well-sorted; angular nature of many of the carbonate grains indicates possible derivation from older limestone. Top of bed forms major dip slope.....	0.3
Pellet calcarenitic limestone, light-brown, tight, partially recrystallized; recrystallization of mud pellets and mud matrix tends to obscure calcarenitic nature of bed.....	0.5
Aphanitic limestone, tan, porous, rarely sandy, chalky; scarce monaxon sponge spicules and scattered molluscan remains and pellets.....	2.6

Total thickness of Buwaib Formation... 17.7

Sulayy Formation.

SECTION 48.—*Qasr Hima*

[Generalized section of Buwaib Formation near Qasr Hima; measurements by R. A. Brankamp, S. J. Roach and S. B. Henry, 1954]

Sandstone of the Biyadh Sandstone (Lower Cretaceous).

	Thickness (meters)
Buwaib Formation:	
Sandstone, yellowish-brown, silty, fine- to medium-grained, friable; common interbeds of light-gray sandy limestone and some reddish-brown dolomite.	8.2
Aphanitic limestone, gray to tan, soft, shaly; common thin interbeds of greenish-gray marl and shale and tan, coarsely skeletal calcarenitic limestone and tightly cemented calcarenite.	14.6
Aphanitic limestone, cream to tan, fossiliferous, platy to rubbly-weathering; occasional thin beds of calcarenite limestone and calcarenite.	22.2
Arab Formation.	

BIYADH SANDSTONE SECTION

SECTION 49.—*Al Biyadh*

[Biyadh Sandstone type section was measured and described by D. A. Holm and N. M. Layne, Jr., in 1949 in Al Biyadh about 20 km south of Wadi Sabhat]

Sandstone of the Wasia Formation (Middle Cretaceous).

Unconformity (not exposed at type locality).

Biyadh Sandstone:

	Thickness (meters)
4. Sandstone (101.8 m thick):	
Covered.	23.8
Sandstone, black-weathering, massive-bedded; forms weak bench.	1.0
Sandstone, poorly exposed, coarse-grained to pebbly.	20.0
Sandstone, gray, nodular-weathering.	1.0
Sandstone, coarse-grained, in part friable, crossbedded; common quartz pebbles.	35.0
Sandstone, gray, sugary, hard, crossbedded.	7.0
Covered; probably friable quartz sandstone; some shale at base.	14.0
3. Shale, limestone, and marl (10.8 m thick):	
Limestone, brown to tan, tight, bench-forming; weathers to black chips on dip slope.	0.5
Shale, green to tan, soft, gypsiferous.	3.7
Marl, tan to buff; forms weak bench.	0.3
Shale, red, sandy.	0.9
Marl, brown to yellow, sandy; forms several weak ledges.	3.3
Shale, red to tan to gray, in part hematitic.	2.1
2. Poorly exposed sandstone (205.2 m thick):	
Sandstone, cream-colored to gray, cross-bedded, fine-grained, sugary, porous, friable.	1.7
Sandstone, coarse-grained, conglomeratic; forms weak bench, weathers to chips of ironstone.	1.8
Covered.	23.0
Sandstone, black-weathering; forms thin ledge.	0.1
Covered.	37.0
Sandstone, brown, coarse-grained; forms low bench.	2.0
Covered; sandy plain.	40.0
Sandstone, gray, massive, tightly cemented.	1.0

SECTION 49.—*Al Biyadh*—Continued

Biyadh Sandstone—Continued

2. Poorly exposed sandstone (205.2 m thick)—Continued

	Thickness (meters)
Covered.	8.0
Sandstone, gray, tightly cemented, massive.	6.0
Poorly exposed; soft shale and sandstone.	43.0
Sandstone, black-weathering, conglomeratic.	0.1
Covered.	6.0
Sandstone, white, massive.	0.5
Covered; probably soft shale and sandstone.	15.0
Sandstone, gray, massive.	1.0
Poorly exposed; red clay shale.	19.0
1. Sandstone (107.2 m thick):	
Sandstone, brown, massive, coarse-grained.	17.0
Covered; probably soft shale and sandstone.	34.0
Ironstone, thin, black-weathering, nodular; caps low hill.	0.1
Shale and sandstone; poorly exposed, gray shale and brown friable sandstone.	15.0
Sandstone, brown, platy; impressions or casts of tree trunks.	4.0
Sandstone, platy, black-weathering; forms low bench.	0.1
Covered; probably friable sandstone; forms flat plain.	11.0
Sandstone, black to brown, platy, ferruginous, nodular.	2.0
Sandstone, brown, iron-stained, coarse-grained.	4.0
Sandstone, brown, massive, coarse-grained.	20.0

Total thickness of Biyadh Sandstone... 425.0
Buwaib Formation.

WASIA FORMATION SECTIONS

SECTION 50.—*Wasi'*

[Wasia Formation type section was measured and described by R. A. Brankamp and S. J. Roach in 1955 at Wasi']

Dolomite of the Aruma Formation (Upper Cretaceous).

Disconformity.

Wasia Formation:

	Thickness (meters)
Sandstone, brown and yellow-weathering, very fine to fine-grained, in part silty; scattered quartz pebbles. Crossbedding is usually well developed except in uppermost part. Fossil wood is present as ferruginous molds.	19.2
Shale, red and purple, silty; some green clay shale, and thin brown to black ironstone partings common. A single 0.1-m-thick reddish-brown sandy, silty dolomite with white-filled vugs at base. Elsewhere nearly similar dolomite layers occur at higher levels. At one locality just east of Wasi' a local lens of cream-colored, colored, nodular, fine-grained limestone up to 2 m in thickness, containing rare ammonites, extends laterally for about 200 m. <i>Neolobites vibrageanus</i> , <i>cidaroid</i> echinoids, and pelecypods occur in carbonate lens.	8.1
Sandstone and siltstone; buff and red-banded, fine-grained; shows small-scale crossbedding.	5.3
Shale, green, brown-weathering, silty sandy.	6.4

SECTION 50.—Wadi '—Continued

	Thickness (meters)
Wasia Formation—Continued	
Sandstone and siltstone; gray, green, and red, relatively thin-bedded, silty fine-grained sandstone and coarse siltstone.....	3.0
Total thickness of Wasia Formation.....	42.0
Biyadh Sandstone.....	

SECTION 51.—Vicinity of Sakakah

[Generalized section of the Wasia (Sakaka) Formation near Sakakah; measurements by D. A. Holm and S. D. Bowers, 1952]

	Approximate Thickness (meters)
Limestone of the Aruma Formation (Upper Cretaceous). Unconformity.....	
Wasia (Sakaka) Formation:	
Siltstone and sandstone; thin, alternating beds of variegated siltstone and off-white to gray, red- to tan-weathering, commonly crossbedded sandstone; some reddish-brown micaceous laminae. Thin layers of ironstone occur at several levels....	100
Sandstone, off-white to gray-brown, brown- and red-weathering, massive, crossbedded, fine- to medium-grained, micaceous; occasional lenses of mottled clay shale.....	145
Sandstone and siltstone; thinly interbedded red, brown, and maroon, friable, fine-grained, cross-bedded micaceous sandstone and siltstone; often lenticular.....	40
Approximate total thickness of Wasia (Sakaka) Formation.....	285
Jauf Formation.....	

ARUMA FORMATION SECTION

SECTION 52.—Wadi al 'Atk

[Aruma Formation type section was measured and described by S. J. Roach in 1952 in area just south of Wadi al 'Atk]

	Thickness (meters)
Dolomite of the Umm er Radhuma Formation (Paleocene and lower Eocene).	
Aruma Formation:	
4. Shale and dolomite (Lima member, 32.9m thick):	
Shale and dolomite; completely interbedded yellow-weathering dolomite shale and pink, blue, and yellow-mottled, platy, impure dolomite.....	14.4
Dolomite, yellow, pink, and blue-mottled, thinly bedded, platy, argillaceous.....	7.8
Dolomite, blue-gray, sucrose crystalline, irregularly bedded; abundant foraminifera.....	3.2
Limestone, tan, gray-weathering, fine-grained; irregular nodular bedding.....	0.5
Marl, greenish-gray, granular, silty.....	2.0
Limestone, cream-colored- to yellow-weathering, granular, massively bedded; thin beds of crystalline, nodular limestone at top and bottom.....	1.0
Shale, brown-weathering, flaky, calcareous; a few limestone nodules.....	4.0

SECTION 52.—Wadi al 'Atk—Continued

	Thickness (meters)
Aruma Formation—Continued	
Disconformity.	
3. Dolomite (upper Atj member, 27.6 m thick):	
Limestone, tan, brown-weathering, detrital and oolitic; a few thin beds of sucrose granular dolomite. Orbitoids and large gastropods locally abundant. Upper part of interval is commonly silicified. Strong bench at top.....	5.0
Dolomite, tan, brown-weathering, sucrose granular, in part argillaceous and rubbly-weathering; scattered patches of oolite and detrital limestone. Forms strong bench at top.....	22.6
2. Limestone (middle Atj member, 41.0 m thick):	
Limestone, cream-colored, tan-weathering, chalky, granular, sparsely detrital, massively bedded, mostly rubbly-weathering; alternately forms strong and weak benches.....	34.6
Limestone, cream-colored, brown-weathering, massively bedded, soft, chalky and slightly argillaceous.....	3.2
Shale, green, brown-weathering, flaky, fissile; in part calcareous varying to a marl and argillaceous limestone along strike. Abundant corals and Foraminifera (<i>Leptunia</i>)....	3.2
1. Calcareous limestone (lower Atj member, 40.0 m thick):	
Molluscan calcareous limestone, tan, brown-weathering; consists of abundant rudistids, oysters, and large gastropods set in matrix of chalky limestone. Bedding is irregular, rubbly weathering, and biotromal.....	6.4
Calcareous limestone, cream-colored, tan-weathering, chalky, nodular; abundant carbonate material.....	16.0
Calcareous limestone, cream-colored, tan-weathering, chalky, nodular; abundant clastic carbonate debris. Nodules are set in a matrix of sandy marl.....	16.0
Dolomite, reddish-brown, dark-red- to brown-weathering, granular, sandy; a few small pebbles and abundant vugs, many filled with white coarsely crystalline calcite.....	1.6
Total thickness of Aruma Formation.....	141.5
Wasia Formation.....	

UMM ER RADHUMA FORMATION SECTION

SECTION 53.—Al Bajin

[Umm er Radhuma Formation reference section was measured and described by W. H. Reim and R. D. MacDougall in 1953 in the Al Bajin channel]

	Thickness (meters)
Sandy limestone of Miocene and Pliocene age.	
Unconformity.....	
Umm er Radhuma Formation:	
2. Calcareous limestone, aphanitic limestone, and dolomite (140.4 m thick):	
Covered.....	2.0
Dolomite, light-brown to gray, medium-grained to finely crystalline; upper 1.0 m shows relic elastic texture.....	4.5

SECTION 53.—*Al Bâjin*—Continued

Umm er Radhuma Formation—Continued

2. Calcarenitic limestone, aphanitic limestone, and dolomite (140.4 m thick)—Continued

	Thickness (meters)
Covered.....	4.2
Dolomite and limestone; brown, medium to coarsely crystalline dolomite alternating with thin beds of pellet calcarenitic limestone and tan soft chalky limestone.....	8.0
Aphanitic limestone, light-gray to tan, vuggy, partially dolomitized; some megafossil shell debris. Upper bed strongly dolomitized and weathers to nodular surface.....	8.5
Calcarenitic limestone, gray to tan, irregularly bedded, partially dolomitized, pellet; total interval has brecciated appearance, rare Foraminifera.....	7.0
Aphanitic limestone, gray-brown, tight, partially dolomitized, commonly fossiliferous; interval capped by thin bed of fine-grained pellet calcarenitic limestone.....	9.0
Calcarenitic limestone, dark-gray, irregularly bedded, fine- to medium-grained, commonly fossiliferous, pellet-detrital; thin bed of brown, friable, coarsely crystalline dolomite at top.....	7.5
Aphanitic limestone, gray, tight, rarely fossiliferous.....	2.8
Calcarenitic limestone, gray, tight, partially dolomitized, pellet-fossiliferous; red-brown to black and cherty on weathered surface.....	3.1
Aphanitic limestone, gray, tight, rather common pelecypod shells.....	0.5
Calcarenitic limestone, gray, tight, in part partially dolomitized, coquinoïd; thin bed of rubbly-weathering dolomite near middle.....	9.2
Aphanitic limestone, gray, finely laminated, tight, hard, siliceous.....	1.2
Calcarenitic limestone, gray, tight, fossiliferous-detrital; pelecypods rather common.....	2.5
Aphanitic limestone, off-white, brittle to partly chalky, slightly siliceous; capped by cherty limestone surface.....	1.0
Marl, off-white to light-yellow, soft, dull, impure, fine-grained.....	1.0
Aphanitic limestone, light-gray, tight, siliceous.....	2.0
Calcarenitic limestone, gray, tight, skeletal.....	2.6
Dolomite, light-gray, tight, finely crystalline; common relic elastic texture. Abundant fossil trash in upper part.....	2.0
Calcarenitic limestone, light-brown, tight, coquinoïd.....	0.5
Aphanitic limestone, light-gray, tight, thinly laminated, chalky, slightly fossiliferous.....	4.7
Dolomite, brown, medium-grained crystalline; weathers dark gray.....	3.7
Aphanitic limestone, light-gray, chalky, slightly fossiliferous, partially dolomitized.....	1.5
Covered.....	2.0
Aphanitic limestone, light-gray, black-mottled, tight, slightly fossiliferous; some patches strongly fossiliferous, siliceous, and partially dolomitized.....	1.6

SECTION 53.—*Al Bâjin*—Continued

Umm er Radhuma Formation—Continued

2. Calcarenitic limestone, aphanitic limestone, and dolomite (140.4 m thick)—Continued

	Thickness (meters)
Covered.....	2.0
Aphanitic limestone, tan to gray, tight, slightly fossiliferous, irregularly bedded, chalky, partially dolomitized; rather rare gastropods throughout and some Foraminifera near top.....	12.8
Calcarenitic, light-gray, moderately friable, skeletal (coquina).....	1.6
Aphanitic limestone, off-white, tight, very thin bedded, fossiliferous; siliceous in upper part becoming chalky in lower; small pelecypods, shell debris, and Foraminifera common.....	2.0
Calcarenitic limestone, light-gray, soft, porous, slightly fossiliferous, in part siliceous, pellet.....	2.6
Aphanitic limestone, yellow, porous, fossiliferous, thinly laminated, alternately chalky and siliceous.....	2.2
Calcarenitic limestone, gray, fossiliferous, pellet.....	2.0
Aphanitic limestone, gray, in part siliceous, fossiliferous.....	4.6
Dolomite, gray, tight, finely crystalline; surface weathers to small nodules.....	1.6
Aphanitic limestone, off-white to gray, tight to slightly porous, rarely fossiliferous, partially dolomitized; large vugs lined with coarse calcite crystals in lower part and common veinlets of calcite in upper.....	3.3
Calcarenitic limestone, gray, tight, coquinoïd; upper part with common pellets.....	4.8
Aphanitic limestone, gray, tight, commonly chalky, partially dolomitized, fossiliferous, rarely siliceous; beds with concentrations of gastropods common.....	7.3
Calcarenitic limestone, gray, tight, coquinoïd.....	1.0
1. Aphanitic limestone (102.7 m thick):	
Aphanitic limestone, gray, tight, partially dolomitized, chalky, commonly fossiliferous; 4.0 m thick covered interval in lower part.....	22.4
Dolomite, blue-gray, tight, fossiliferous, very finely crystalline; common vugs and rare small gastropods and pelecypods.....	5.7
Covered.....	3.2
Dolomite, gray, tight, finely crystalline; weathers gray to black.....	1.0
Covered.....	1.8
Dolomite, gray, mottled black, fossiliferous, finely crystalline; fossils completely replaced by dolomite.....	1.6
Aphanitic limestone, off-white to light-gray, thin-bedded, partially dolomitized, chalky, commonly fossiliferous; poorly exposed in lower part.....	18.2
Aphanitic limestone, mostly concealed, probably white, chalky.....	3.2

SECTION 53.—*Al Bajin*—Continued

Umm er Radhuma Formation—Continued

1. Aphantic limestone (102.7 m thick):

	Thickness (meters)
Aphantic limestone, off-white to light-gray, limonite stained in lower part, commonly fossiliferous, chalky, rarely siliceous; gastropods and pelecypods at several levels, rare Foraminifera throughout. Rare vugs.	34.4
Aphantic limestone, dark-gray, tight, vuggy, platy-weathering, strongly dolomitized, in part siliceous; conchoidal fracture.	3.0
Aphantic limestone, mottled tan and dark-gray, rubbly-weathering, tight, partially dolomitized; vermiform weathering surface in lower 2.0 m. Rare, poorly preserved Foraminifera.	7.2
Dolomite, dark-gray to yellow and white-mottled, tight, sugary, finely crystalline; off-white to tan nodular weathered surface.	1.0

Total thickness of Umm er Radhuma Formation..... 243.1

Aruma Formation.

RUS FORMATION SECTION

SECTION 54.—*Umm ar Ru'ud*

[Rus Formation type section was measured and described by R. A. Brankamp in 1946 at Umm ar Ru'ud]

Shale (lower Eocene) of Damman Formation.

	Thickness (meters)
Rus Formation:	
3. Limestone, white, soft, chalky, porous; several thin beds of calcarenite at top.	3.6
2. Marl and limestone; light-colored marl with local irregular masses of crystalline gypsum and occasional thin harder limestone beds; geodal quartz is present at several levels.	31.8
1. Limestone, gray to buff, compact, commonly partially dolomitized; minor beds of soft limestone made porous by leaching of small organic remains. Rare quartz geodes in lower part and are typical of uppermost beds.	21.0
Total thickness of Rus Formation.	56.4
Dolomite of the Umm er Radhuma Formation.	

DAMMAM FORMATION SECTION

SECTION 55.—*Near Dhahran*

[Damman Formation reference section was measured and described by R. W. Powers, M. C. Coffield, and H. W. Schneider in 1933 in the vicinity of Dhahran]

Sandy limestone of the Hadhrukh Formation (lower Miocene?). Unconformity.

Damman Formation:

	Thickness (meters)
Alat Member (15.0 m thick):	
Limestone, cream-colored to tan, chalky, porous, commonly dolomite; abundant molds of molluscs and other indeterminate organic debris.	9.0
Marl, light-colored, commonly cream-colored—orange in subsurface—locally strongly argillaceous, dolomite; abundant discrete dolomite rhombs set in marl or clay matrix.	6.0

SECTION 55.—*Near Dhahran*—Continued

Damman Formation—Continued

Khobar Member (9.3 m thick):

	Thickness (meters)
Limestone, light-brown, partially recrystallized, tight, nummulitic.	3.0
Limestone, yellow-brown, soft, marly.	1.2
Limestone, off-white, partially recrystallized, tight, nummulitic.	3.6
Marl, off-white to tan, dolomitic.	1.5
Alveolina Limestone Member (1.0 m thick):	
Limestone, light-tan, partially recrystallized, tight; abundant <i>Alveolina ekipian</i> var. <i>foveolata</i> .	1.0
Saila Shale Member (4.2 m thick):	
Shale, dark-brownish-yellow, subfossil clay-shale.	3.6
Limestone, gray-buff, tight, <i>Alveolina</i> cf. <i>A. decipiens</i> common.	0.6
Midra Shale Member (3.0 m thick):	
Shale, yellow-brown, fissile, very thinly laminated.	3.0

Total thickness of Damman Formation.... 32.5
Rus Formation.

HADHRUKH FORMATION SECTION

SECTION 56.—*Jabal al Haydarukh*

[Hadhrukh Formation type section was measured and described by Max Steineke and T. W. Koeh in 1933 at Jabal al Haydarukh]

Limestone of the Dam Formation (middle? Miocene).

	Thickness (meters)
Hadhrukh Formation:	
Sandstone, buff, coarse-grained, fossiliferous; abundant calcite crystals, fish and echinoderm remains.	3.8
Marl, white, conglomeratic.	0.5
Sandstone, buff to yellow-green.	1.5
Clay, green.	2.8
Sandstone, gray-green, medium-grained.	0.3
Clay, green.	1.8
Gypsum and abundant chert; becomes marly eastward.	1.6
Sandstone, green, medium-grained.	1.8
Clay, green, gypsiferous.	1.5
Sandstone, buff, fine-grained, marly.	3.3
Sandstone, buff and brown, medium-grained.	5.0
Marl, white, platy-weathering.	1.0
Clay and sandstone; alternating green clay and gypsiferous sandstone; abundant chert concretions.	5.0
Marl, white, clayey.	0.3
Clay and sandstone; alternating green clay and medium-grained sandstone; abundant chert concretions.	3.0
Clay and sandstone; green gypsiferous clay and fine-grained sandstone; abundant chert.	1.6
Sandstone, buff and gray, medium-grained, marly.	1.6
Clay, green; thin bed of green fine-grained friable gypsiferous sandstone in middle.	4.0
Sandstone, green, hard.	5.6
Sandstone, green, fine-grained, friable; common laminations of green clay, gypsum, and chert.	2.5
Sandstone and marl; white marly sandstone and conglomeratic marl.	2.0
Sandstone, very coarse-grained to pebbly.	1.0

SECTION 56.—*Jabal al Haydarik*—Continued

Hadruk Formation—Continued

Marl, gray, very sandy; occasional thin beds of off-white sandy limestone and tan friable sandstone.....	32.5
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Total thickness of Hadruk Formation.....	84.0
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Damman Formation.

DAM FORMATION SECTION

SECTION 57.—*Jabal al Lidam*(Dam Formation type section measured and described by Max Steineke and T. W. Koch in 1935 at *Jabal al Lidam*.)

Clay of the Hofuf Formation (Miocene or Pliocene).

Dam Formation:	Thickness (meters)
Marl, gray, fragmental, fossiliferous.....	1.0
Marl, pink, strongly argillaceous.....	1.0
Marl, white, tough.....	1.0
Clay and sandstone; red and green sandy and silty clay and red sandstone.....	8.0
Marl, buff to white, pebbly; abundant red marl fragments. Thin bed of conglomerate at top.....	1.7
Marl, white, chalky.....	1.6
Chalk and sandstone; white chalk and gray cross-bedded sandstone; fossils at base.....	1.0
Marl, gray and buff, thin-bedded, fossiliferous.....	1.0
Marl and clay; white marl and green clay.....	1.8
Marl and clay; yellow fossiliferous marl and green clay.....	1.0
Sandstone and marl; gray-green sandstone and buff conglomeratic fossiliferous marl.....	1.0
Clay, green.....	7.5
Covered.....	0.5
Limestone and marl; tan tight sandy limestone and buff fossiliferous marl.....	1.4
Marl, limestone, and sandstone; buff and white marl, yellow fossiliferous limestone and sandstone.....	12.6
Covered.....	0.5
Limestone, tan, sandy.....	0.5
Marl, greenish-tan, fossiliferous, sandy.....	2.6
Sandstone, greenish-yellow.....	1.0
Marl, white, chalky.....	0.2
Marl and sandstone; white tough foraminiferal marl and gray oolitic sandstone.....	2.0
Marl, white, fossiliferous.....	8.8
Marl, off-white to yellow, chalky, sandy, fossiliferous; Foraminifera common.....	4.8
Limestone, tan, marly, fossiliferous; abundant Foraminifera.....	3.6
Marl, buff and white, tough.....	1.0
Clay, green.....	1.8
Limestone, greenish-tan, fossiliferous, sandy.....	1.8
Marl, greenish-gray, fossiliferous, chalky.....	7.3
Marl, abundant echinoid form "Button bed" essentially an echinoid coquina.....	1.0
Marl, white, chalky, foraminiferal.....	3.5
Sandstone, marly.....	2.0
Marl, buff, fossiliferous.....	1.5
Sandstone, hard, oolitic; few fossils.....	1.0
Sandstone, white, very fossiliferous, marly; few echinoids.....	2.8
Clay, green.....	0.5
Marl and sandstone; white sandy marl and marly sandstone.....	0.5

Total thickness of Dam Formation.....	90.8
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Hadruk Formation.

HOFUF FORMATION SECTION

SECTION 58.—*Near Al Hufuf*

(Hofuf Formation type section was measured and described by Max Steineke and T. W. Koch in 1935 near Al Hufuf.)

Surficial deposits (Quaternary).

Unconformity.

Hofuf Formation:

	Thickness (meters)
4. Conglomerate (9.1 m thick): Conglomerate, gray, marly, limestone; limestone boulders in marly quartz sand matrix.....	9.1
3. Sandstone (48.6 m thick): Sandstone, alternating red and white, argillaceous.....	48.6
2. Limestone (18.2 m thick): Limestone, white, chalky, sandy; weathers to granular calcitic sand.....	16.2
Limestone, brown, bench-forming.....	2.0
1. Conglomerate (19.1 m thick): Conglomerate; red and white limestone boulder and pebble.....	17.1
Marl, mottled greenish-gray and reddish-brown.....	2.0

Total thickness of Hofuf Formation.....	95.0
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Dam Formation.

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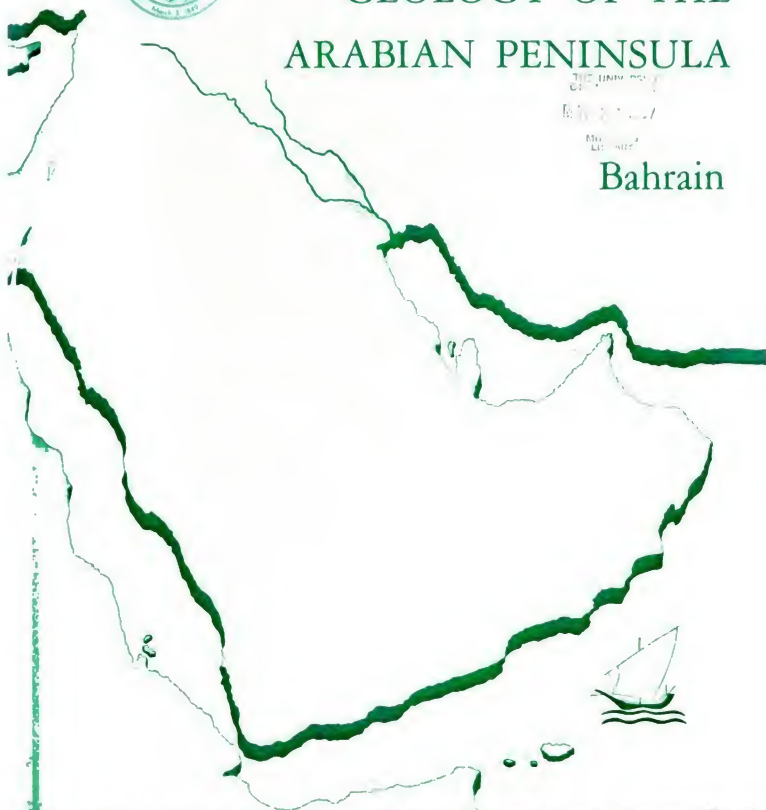
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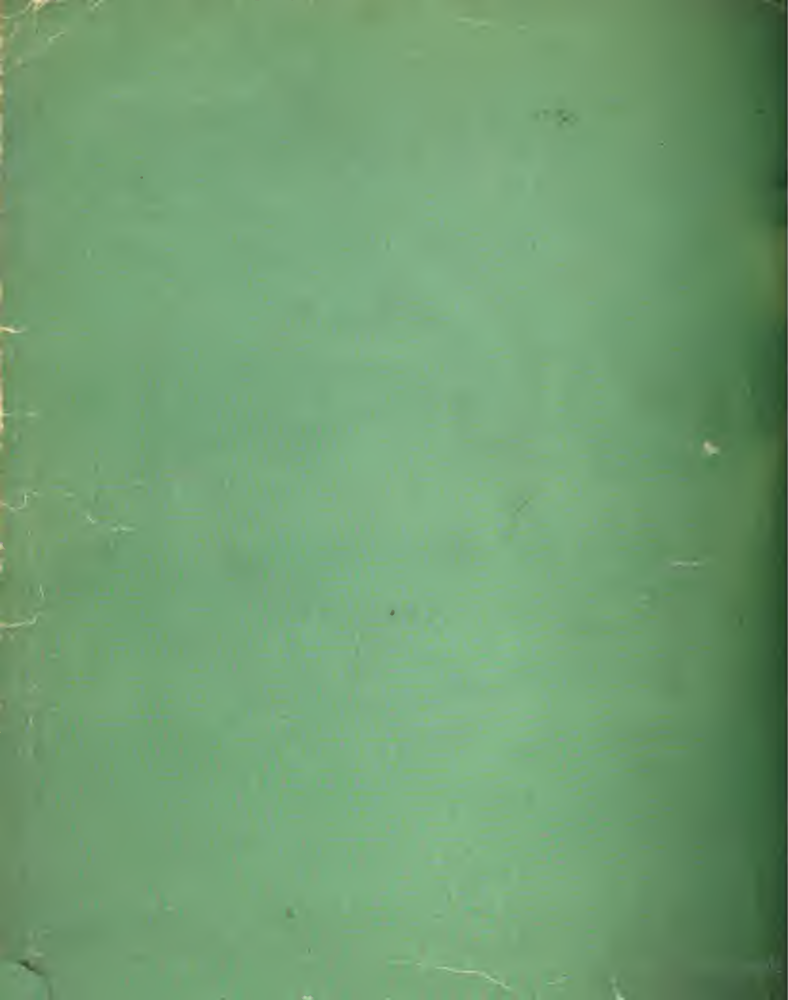
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GEOLOGY OF THE ARABIAN PENINSULA

THE UNITED STATES
GEOLOGICAL SURVEY

WASHINGTON, D. C.

1905

Bahrain

Geology of the Arabian Peninsula

Bahrain

By R. P. WILLIS

GEOLOGICAL SURVEY PROFESSIONAL PAPER 560-E

*A review of the geology of Bahrain as shown on
USGS Miscellaneous Geologic Investigations Map
I-270 A, "Geologic Map of the Arabian Peninsula," 1963*



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GEOLOGICAL SURVEY

William T. Pecora, *Director*

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FOREWORD

This volume, "*The Geology of the Arabian Peninsula*," is a logical consequence of the geographic and geologic mapping project of the Arabian Peninsula, a cooperative venture between the Kingdom of Saudi Arabia and the Government of the United States. The Arabian-American Oil Co. and the U.S. Geological Survey did the fieldwork within the Kingdom of Saudi Arabia, and, with the approval of the governments of neighboring countries, a number of other oil companies contributed additional mapping to complete the coverage of the whole of the Arabian Peninsula. So far as we are aware, this is a unique experiment in geological cooperation among several governments, petroleum companies, and individuals.

The plan for a cooperative mapping project was originally conceived in July 1953 by the late William E. Wrather, then Director of the U.S. Geological Survey, the late James Terry Duce, then Vice President of Aramco, and the late E. L. deGolyer. George Wadsworth, then U.S. Ambassador to Saudi Arabia, and Sheikh Abdullah Sulaiman, then Minister of Finance of the Government of Saudi Arabia, lent their support to the plan. In November of the following year, 1954, Director Wrather approved the U.S. Geological Survey's participation and designated G. F. Brown responsible for the western Arabian shield region in which he had previously worked under U.S. foreign-aid programs. In January 1955 F. A. Davies, Chairman, Board of Directors, Arabian-American Oil Co., approved Aramco's participation and appointed the late R. A. Bramkamp, chief geologist, responsible for compilation of the area within the Kingdom where the sediments crop out. This responsibility fell to L. F. Ramirez following the death of R. A. Bramkamp in September 1958.

R. A. Bramkamp and G. F. Brown met in New York in February 1955 and planned the program, including scales of maps, areas of responsibility, types of terrain representation, and bilingual names. Thus there was established a cooperative agreement between the Kingdom of Saudi Arabia, the U.S. Department of State, and the Arabian-American Oil Co. to make available the basic areal geology as mapped by Aramco and the U.S. Geological Survey.

The agreement specified publication of a series of 21 maps on a scale of 1:500,000, each map covering an area 3° of longitude and 4° of latitude. Separate geologic and geographic versions were to be printed for each of the quadrangles; both versions were to be bilingual—in Arabic and English. A peninsular geologic map on a scale of 1:2,000,000 was to conclude the project.

High-altitude photography, on a scale of 1:60,000, of the Kingdom of Saudi Arabia was initiated during 1949 by the Aero Service Corp. and completed in 1959. Both third-order vertical and horizontal control and shoran were utilized in compiling the photography. This controlled photography resulted in highly accurate geographic maps at the publication scale which then served as a base for the geologic overlay. The topography of the sedimentary areas was depicted by hachuring and that of the shield region by shaded relief utilizing the airbrush technique.

The first geographic quadrangle was published in July 1956 and the last in September 1962. While preparation of the geographic sheets was in progress, a need arose for early publication of a 1:2,000,000-scale peninsular geographic map. Consequently, a preliminary edition was compiled and published in both English and Arabic in 1955. The second edition, containing additional photography and considerable new topographic and cultural data, was published in 1963. The first of the geologic map series was published in July 1956 and the final sheet in early 1964. The cooperative map project was completed in October 1963 with the publication of the 1:2,000,000-scale "Geologic Map of the Arabian Peninsula" (Miscellaneous Geologic Investigations Map I-270 A).

As work on the quadrangles progressed, geologists, companies, and governments working in areas adjacent to the Kingdom of Saudi Arabia were consulted by Aramco and invited to participate in the mapping project. The number of cooperating participants was expanded to 11, which included the operating oil companies in the peninsula and which are identified elsewhere in this text; the Overseas Geological Surveys, London; the Government of Jordan; F. Geukens, who had worked in Yemen; and Z. R. Beydoun, who had studied the Eastern Aden Protectorate. With the close cooperation of the authors, the new data were added to data already plotted on the base map of the Arabian Peninsula.

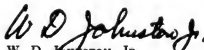
As the geological coverage of the peninsular map grew, the need for a text to accompany the map became apparent to both the U.S. Geological Survey and the Aramco geologists. Exploratory conversations were begun by Aramco with companies working in the other countries of the Arabian Peninsula for their participation in the preparation of a monograph on the geology of the Arabian Peninsula. Each author prepared a description of the geology of the area for which he was responsible, as shown in the sources of geologic compilation diagram on the peninsular map. The U.S. Geological Survey undertook the publishing of the volume as a professional paper, and the Government of Saudi Arabia was to finance its printing. It was early agreed that there would be no effort to confine the contributions to a standard format and that no attempt would be made to work out an overall correlation chart other than shown on the "Geologic Map of the Arabian Peninsula." Thus, the individual style of authors of several nationalities is preserved.

Cooperation and relations have been of the highest order in all phases of the work. The project would not have been possible without the full support of the U.S. Department of State, the Kingdom of Saudi Arabia, and all contributors. In fact, the funds which made publication of this volume possible were contributed by the Saudi Arabian Government.

The data provided by the maps and in the professional paper provide information for an orderly scientific and economic development of a subcontinent.



O. A. SAGER,
Arabian-American Oil Co. (Retired).



W. D. JOHNSTON, JR.,
*Former Chief, Foreign Geology Branch,
U.S. Geological Survey.*

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 2. Schematized regional correlation of rock units, southern Iraq.
 3. Tentative subsurface stratigraphic correlation in southwestern Iraq-Kuwait.
 4. Diagrammatic regional geologic section across southern Iraq.

FIGURE 1. Tectonic map of Iraq.....

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G50

GEOLOGY OF THE ARABIAN PENINSULA

SOUTHWESTERN IRAQ

By K. M. AL NAQIB¹

ABSTRACT

Southwestern Iraq covers all Iraqi territory south of lat 32° N. and west of the Euphrates River. Slightly to the north, the area's oldest rocks (Lower Triassic?) crop out in the Ga'ara depression where they are succeeded by Middle and Upper Triassic, Rhaetic, and Lower and Middle Jurassic rocks. The Middle Jurassic sequence is unconformably overlain by Cenomanian sandstones and limestones; the gap in sedimentation diminishes away from the Ga'ara area. The Cenomanian deposits are succeeded by Upper Cretaceous limestone. The Cretaceous sedimentation in southwestern Iraq was due to periodic epeirogenetic withdrawals, which are reflected in a series of sedimentary cycles characterized by strong diachronism of the sediments. A sequence of Paleocene and Eocene deposits covers most of the area in long scarp strips. On the east side the Miocene limestones, evaporites, and clastics overlap the Eocene beds. The Miocene limestone overstepping, however, seems to be more extensive and covers large areas in the west. Oligocene deposits are not recognized in the area, indicating a major pre-Miocene unconformity. The Pliocene and Pleistocene sequence covers the southeastern part of the area, the transition from Miocene to Pliocene deposition seems to be gradational. Descriptions of 27 formations have been made in some detail.

Structurally, the area constitutes a small part of the Interior Homocline of the Arabian Peninsula. It is simple, flat-lying country with very gentle dips to the east and northeast. There are a few depressions in the central parts which may be indicative of deeply buried graben systems accentuated by the solution-collapse effects. There is evidence of relatively strong movements during the Cenomanian and early Miocene times, which influenced the realms of sedimentation more than the epeirogenetic movements during Cretaceous and Tertiary times. In southern Iraq these movements are still active and influence the retreat of the Persian Gulf. Minor linear structural elements, oriented north-northwest and north, occur in the area of Tertiary outcrops. These were possibly initiated on deeply buried old faults which were activated by recent disturbances.

Oil was found in commercial quantities in the sand reservoirs of the Zubair Formation, in the Zubair and Rumaila fields, after considerable effort, energy, and investment by the Iraq Petroleum Company, Ltd., and its associate the Basrah Petroleum Company, Ltd.

¹ Of the Iraq Petroleum Company, Ltd.

INTRODUCTION

The area of present review covers a territory of more than 82,000 square kilometers lying south of lat 32° N., and is limited by the Euphrates and Shatt al Arab Rivers on the east and by the Iraq-Saudi Arabia and Iraq-Kuwait borders on the west and south.

During the early 19th century many scientists and scholars who were interested in the archaeology of southern Iraq, a classic area, attempted to explain their findings geologically. Beke (1835) described the geological evidence of the advance of the land at the head of the Persian Gulf and commented on the alluvium of Babylonia and Chaldaea. Ainsworth (1838) gave the geological results of the Euphrates Expedition which was conducted by Colonel Chesney.

With increased demand for oil, interest in the petroliferous area of Mesopotamia and in its geology grew. In 1905, H. Bücking, C. Porro, and Kissling reported on the seepage areas of the Euphrates and Tigris Rivers. Two years later, P. Grosskoff reported on the petroleum deposits of the area for the Turkish Civil List. Geological interest increased and authorities such as Pascoe (1922) made more serious and prolonged surveys and evaluations of the general area. G. W. Halse in 1918 examined the bituminous districts west of Euphrates River.

These surveys in southwestern Iraq, however, were only reconnaissance in nature. Greater attention to the geology of western Iraq was paid by A. H. Noble and L. D. Evans, who spent parts of 1919 and 1920 conducting a general geological reconnaissance of Iraq, the primary aims of which were the establishment of a stratigraphic section for the area and the investigation of the most important structures from the point of view of petroleum.

With the 1925 Oil Concession agreement, the Turkish Petroleum Company, Ltd. (later renamed the Iraq Petroleum Company, Ltd.), commenced an intensive geological reconnaissance in Iraq. In the course of

this, H. de Boeckh, who had made some investigation in western Iraq in 1924, revisited the area in the spring of 1925 with S. L. James, G. M. Lees, and F. D. S. Richardson. During 1925-29 A. C. Trowbridge, E. W. Shaw, A. H. Noble, Bouchier, and H. De Boeckh undertook general geological reconnaissance and inspection of the possible oil prospects in western Iraq. Exploratory activities were cut back in 1929 after a decision was made to devote all available resources to the development of the Kirkuk field, where oil had been struck in October 1927.

Interest in the western desert was not confined to petroleum exploration alone. Geologists were intermittently active in investigating potential groundwater supply. An excellent work reporting on the progress of hydrological inquiries in the area was made by W. A. Macfadyen and S. D. Bekhor during April and May 1934. Macfadyen (1938) described the geology of the area in some detail, discussing both stratigraphy and structure in relation to water resources.

Interest in the petroleum possibilities of southern Iraq led to the incorporation, on July 22, 1938, of the Bashrah Petroleum Company, Ltd., an associate of Iraq Petroleum Company, Ltd. A week later a convention was made with the government of Iraq, whereby the Company was granted a 75-year oil concession covering southern Iraq, which extended from the 33d parallel southward to the borders of Iran, Kuwait, and Saudi Arabia. The area of the present review, which comprises most of the southern desert west of the Euphrates River, together with the District of Brasa, occupies the western and southern part of this concession. The convention became operative on November 30, 1938, on which date its ratifying law was published in the Iraqi Government Gazette. Article 4 of the convention required the Company to conduct a detailed geological survey before July 30, 1939.

Company geological field parties and a torsion-balance survey party under contract from the Torsion Exploration Co., Texas, began operations in the area in January and March of 1939, respectively. This early geological investigation varied in scope and nature; it embraced reconnaissance geologic mapping as well as detailed mapping of selected areas and stratigraphic as well as structural studies. It included systematic aerial reconnaissance as well as topographic surveying. The geological field parties operated continuously until May 1941, when exploration was temporarily suspended because of civil disturbances within Iraq and because of the general stringencies imposed by world war. By this date a considerable area of the western desert of Iraq had been examined by geo-

logists. The early investigators in this field included T. F. Williamson, D. C. Rogers, W. T. Foran, H. L. Thompson, H. Hotchkiss, H. Huber, H. Badoux, and F. Kubba under the general direction of the Chief Geologist, N. E. Baker. In September 1940 the torsion-balance party was replaced by a gravimeter party from the Mott Smith Corp., Texas, which left Iraq in April 1941 at the time of the revolt.

During the war years attention was chiefly paid to solving difficult, detailed problems of stratigraphy, partly through laboratory studies of samples collected prior to 1941. Fieldwork was on a restricted scale because of the shortage of staff.

During the years following World War II, geological exploration activities continued in the southern desert. Geological field parties engaged in detailed structural mapping, stratigraphic investigations, and reconnaissance surveying. These were supported by photogeological and topographical surveys and by a limited program of structural drilling of shallow holes with an M. I. Failing rig. The structure drilling was restricted to selected areas such as Luqait, Shagra, Abu Ghar, Takhadid, Dimana, and Galaib and had as its objectives the investigation of gravity anomalies, the confirmation of localized structures, and the clarification of facies changes. Field investigations were discontinued when the Iraqi Government ordered suspension of the Company's exploratory activities in April 1961 as a result of the breakdown of oil negotiations. During the period 1946-61 a great many Company geologists, under the successive guidance of N. E. Baker, F. E. Wellings, and C. E. Thiebaud, contributed to the geological knowledge of the area through field investigations, subsurface studies, laboratory and stratigraphic correlations, and paleontological studies. These contributors, whose work is contained for the most part in unpublished reports of the Company, include C. Andre, A. S. Abbo, R. V. Browne, R. C. van Bellen, Z. R. Beydoun, M. Chatton, J. M. Cox, E. J. Daniel, H. V. Dunnington, E. K. Elliott, G. F. Elliott, H. A. Field, T. Fothergill, D. Glynn Jones, A. S. Halliwell, E. Hart, F. R. S. Benson, J. M. Hudson, R. G. S. Hudson, J. P. Jaccard, A. V. James, K. D. Jones, F. A. Al Kasim, A. P. Leggat, J. McGinty, J. M. Macleod, S. Marchant, S. C. McKinley, G. Medaisko, D. M. Morton, K. M. Al Naqib, S. Nasr, R. M. V. Rabanit, R. M. Ramsden, M. Roy, I. Rolleigh, A. Th. C. Rutgers, V. M. Safar, H. M. Saleh, A. S. Sayyab, A. H. Smout, T. P. Storey, W. Sugden, K. F. M. Thompson, F. J. Venn, P. Walmsley, R. Wetzel, and E. Williams-Mitchell. Non-Company geologists who published reports on the geology of the region are included in the bibliography.

Geophysical work by a combined gravity and magnetic survey party recommenced after the war years in November 1945, the first area to be investigated being Zubair. In the following year, geophysical activities were increased to a scale greater than at any time since 1940. Three geophysical survey parties (one seismic and two gravity and magnetic) of the Robert Ray Co. were engaged on extensive exploratory work in the western desert during 1948 and 1949. Seismic parties of the Independent Exploration Co., Ltd., London, using reflection and refraction techniques, were also deployed in this area. In 1951 two double gravity-magnetic geophysical parties of the Robert Ray Co., and one party of Seismograph Services, Ltd., operated intermittently in the area and were employed in different parts of Iraq according to season. The geophysical surveys were supplemented by topographic as well as aerial surveys. The geophysical investigation continued at about this intensity through ensuing years. In June 1956 the Company, in addition to the contractors' crews, organized its own seismic crew which started operation near Karbala.

After the Suez crisis and sabotage of the Syrian pipelines in 1956, exploration activity was reduced during 1957. However, during the following years, until the suspension of exploration by order of the Iraqi Government in April 1961, full-scale exploratory activities were carried on. By 1964 the gravity survey had covered the entire area of the present review, while seismic-survey coverage was largely confined to particular areas for example, Basra, Qasr Shagrah district, and Shawiyat.

The results of the early geophysical surveys suggested the existence of some potential oil-bearing structures. Accordingly, test wells were drilled on the most promising of them at Zubair No. 1 (Feb. 14, 1948, to Mar. 13, 1948), Nahr Umr No. 1 (Mar. 23, 1948, to Feb. 13, 1949), and Ratawi No. 1 (Nov. 30, 1948, to Mar. 18, 1950). The first two wells penetrated oil sands, Zubair No. 1 between 10,200 and 11,100 feet and Nahr Umr No. 1 below 8,000 feet. In September 1948 the Iraq Petroleum Company informed the Government that oil in commercial quantities had been discovered. More wells were drilled at both places, but the second well at Nahr Umr encountered water; to produce oil for export at the earliest possible time, all the drilling efforts were concentrated at Zubair.

Drilling activities were greatly intensified during 1950, and the transition from exploratory operations to the development of the Zubair field was accomplished. By the end of the year the laying and welding of the entire Zubair-Fao 12-16-inch pipeline was completed, and work on terminal and field installations

and facilities was progressing well. At the end of 1951 the first jetty (No. 3) at Fao was completed, together with berthing and mooring dolphins. The *M. V. Niso* was the first ship to berth at the jetty. She sailed with a cargo of 11,043 tons of oil on December 21, 1951. The official inauguration of production from the Zubair field took place on January 10, 1952. In February of the same year, a 50-50 profit-sharing agreement, negotiated in 1951, was approved by the Iraqi Chamber of Deputies and ratified by the Senate, retroactive to January 1951.

Prior to the commencement of production, 12 wells had been completed in the Zubair field. The increasing exploratory activities of the Company were rewarded by the discovery in 1953 of the Rumaila field, 20 miles west of Zubair. Drilling on a geophysical prospect began on February 21, 1953, and oil was found in the first well, under conditions similar to those prevailing at Zubair.

With this discovery, attention in the following years was directed to the development of the Rumaila field. For the purposes of immediate production, however, reliance was mainly placed on Zubair, where 38 wells had already been completed. The Company switched the emphasis of its activities from Zubair to the development of the Rumaila field in 1955, with the object of increasing the production rate to 8 million tons per year.

In 1953 a 24-inch pipeline was laid between Zubair and Fao. As the development progressed as planned, some effort reverted to exploratory drilling. The exploratory well Rachi No. 1 (June 11, 1956, to Jan. 11, 1957) was drilled to a depth of 12,959 feet, but the results were disappointing. Exploration activities were intensified, and the western desert received further attention which continued until the suspension of exploration in April 1961.

During this period the following wells were drilled west of the Euphrates River: Samawa No. 1 (Aug. 31, 1958 to Nov. 9, 1959); drilled to a depth of 12,602 feet, was plugged back owing to disappointing results; Tuba No. 1 (Mar. 3, to Dec. 27, 1959), on reaching depth of 11,940 feet, was completed as an observation well; and Nahr Umr No. 3 (Mar. 2 to Oct. 11, 1958), with a total depth of 10,109 feet, found oil in the Nahr Umr sands. North-northwest of An Najaf, two wells—Kifl No. 1 (Sept. 21, 1959, to July 8, 1960) and Kifl No. 2 (Jan. 23, to Feb. 28, 1961)—were drilled to total depths of 10,681 and 6,293 feet, respectively, some oil having been found in the Zubair Formation in the first well.

On the deep wells Ideal 100 rigs were used. However, an H 525 Rambler rig was used to drill shallow

stratigraphic and structural test wells such as Shawiya No. 1, Ghalaisan No. 1, Safawi No. 1, and Ubaid No. 1, which did not exceed 6,000 feet in depth. Shawiya No. 1 (Feb. 15, to Apr. 20, 1960), which was completed at a depth of 5,853 feet, found the Zubair Formation waterlogged. Except for the presence of some gas in the Nahr Umr Formation, the findings were similar in Ubaid No. 1 (Nov. 2, to Dec. 12, 1960), which was completed at a depth of 6,050 feet. The results of the wells Ghalaisan No. 1 (May 15, to July 25, 1960; 6,533 ft) and Safawi No. 1 (Aug. 17, to Oct. 9, 1960; 6,000 ft) were also disappointing, but oil in good quantity was found in the Zubair Formation in Luhais No. 1 (Jan. 17, to Apr. 15, 1961). This well was plugged at a depth of 9,646 feet after the general suspension of exploration in April 1961.

By 1964 there were 39 wells in each of the two oil fields of Rumaila and Zubair. The productive length of the Rumaila fields has proved to be at least 60 kilometers.

Oil production from these fields is maintained by an elaborate modern system of pipelines, degassing stations, tank farms, and oil-terminal facilities. A 16-inch pipeline between Rumaila and Zubair was commissioned in October 1957. To handle an envisaged increase in production rate, the deep-water terminal of Khor al Amaya was constructed in the Arabian Gulf during 1959-62, and a 30- to 32-inch pipeline between Zubair and Foa was laid parallel to the 24-inch pipeline. The old 12-16-inch pipeline was realigned and converted for gas transmission.

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The author has drawn freely on unpublished Company reports of many colleagues and on papers by authors mentioned in the bibliography. Contributions from all these sources are gratefully acknowledged.

GENERAL GEOMORPHOLOGY

Southwestern Iraq as a whole is relatively flat, though there are very gradual and gentle rises in altitude from east to west and from south to north. The rise in altitude along the Shatt al Arab and Euphrates Rivers is gentle, between Al Faw (Fao) and Bahr al Mill, west of Karbala, amounting to only 245 feet (74.6 meters), whereas southwestward from Al Basrah on the Shatt al Arab to the Iraq-Saudi Arabia Neutral Zone, the rise in altitude is five times as great in about one third of the distance. In the extreme west, at Jabal Unazah (Aneiza), where the borders of Iraq, Saudi Arabia, and Jordan intersect, altitudes are as much as 3,084 feet (940.1 m) above sea level. Even here, the region has a general east-northeast slope, toward the Euphrates—the only perennial river.

The region has been subdivided by various authors into a number of physiographic areas (Macfadyen, 1938; Mitchell, 1956). For purposes of the present review the following subdivisions are recognized:

Mesopotamian alluvial plain covers the area between the Euphrates and Tigris Rivers and comprises flat country surfaced by Recent alluvium (or locally by the marine Hammar Formation).

Sand dune belt, according to Macfadyen (1938), forms an area 10-15 kilometers wide on the east border of the southern desert of Iraq, and separates it from the Euphrates River. It extends from south of An Najaf to the Wadi Batin in the extreme south.

Ad Dibdibba gravel and sand region occupies the southern part of Iraq and is bounded roughly to the north and west by Jaliba, Abu Ghar, Al Busayyah, Jahmah, B'ir Juraybi'at, and Al Waqia. Outlying areas of physiographic similarity are to be found near An Najaf and Karbala, in the north.

Al Hajara limestone region includes most of the area under review. The surface is largely made up of limestone outcrops, at some places obscured and littered with residual flints and cherts.

Al Widyaa country covers a large area south of the Ga'ara in lat 33°30' N, and west of long 43° E. It consists of a vast plain gently rising westward so as to appear almost flat. The geomorphic expression of the region is largely a function of the geologic framework of the area and particularly of the lithologic characteristics of the constituent outcrops. The different physiographic belts or areas are discussed below in some detail.

MESOPOTAMIAN ALLUVIAL PLAIN

In southwestern Iraq the Mesopotamian alluvial plain extends west of the Euphrates River as a narrow belt and consists of mudflats and sabkhas, which receive the drainage of the numerous shaihs and wadis

during the wet season. The sabkhas are soft rather saline mudflats, which in many places hold moisture even through the dry season; they are, as a result, very difficult to cross. They cover extensive areas between Ur Junction and As Samawah, and hinder transport from the desert to the railway. In the south, sabkhas also occur along the margins of Hawr al Hammar; they extend northward as far as An Najaf. Their magnitude and characteristics vary from place to place.

SAND-DUNE BELT

The rather mobile sand-dune belt covers the eastern part of the territory. It may transgress to any of the other adjacent physiographic zones, the Mesopotamian plain, Al Hajara, or the Dibdibba.

AD DIBDIBBA GRAVEL AND SAND REGION

The Ad Dibdibba zone is distinctive in its physiography; it is largely flat, low, and scrub covered. The Wadi Batin, cut into the Dibdibba plain, forms a conspicuous negative feature which defines part of the Iraq-Kuwait boundary. In southwestern Iraq the Dibdibba extends westward from the Shatt al Arab and Euphrates (Hawr al Hammar) Rivers in the east to the vicinity of Qasr Shaqrah and Al Busayyah and into the Iraq-Saudi Arabia Neutral Zone. Here the terrain is rather flat, having but a few slightly higher isolated elongated hills. The country is covered with gravel and sand. The gravels are of various igneous and quartz pebbles, and the coarse sands are in places cemented into hard grit.

South-southwest of Az Zubair village and very close to the Iraq-Kuwait border, the Jabal Sanam stands out as a solitary and isolated hill. It has an altitude of more than 500 feet in a low-lying region whose altitude elsewhere ranges between 50 and 150 feet above sea level. This prominent and impressive feature is a piercement salt dome (the only one in Iraq), the detailed geology of which is still obscure. The drainage system of Ad Dibdibba is apparently controlled by the Boliya-Ar Rachi topographic feature. The surface is sandy and gravelly with good porosity; and because the rainfall is generally slight, drainage lines have not been significantly incised, except for the long, deep, and very straight Wadi Al Batin, which runs north-eastward. The other shaibs and wadi courses on the east side of the Boliya feature show a gradual swing in direction northeast to north toward Hawr al Hammar, as evidenced in Shaib ash Shich, Shaib al Ubtaim (Butayn), and Shaib al Adhibi. Most of the courses west of the Boliya-Ar Rachi feature end in gentle closed depressions, forming a kind of internal drainage basin, such as that at Khor Ashi Shihiyat.

AL HAJARA LIMESTONE REGION

The Al Hajara region takes its name from the weathered rocky limestone terrane of Huweimi and Shawiya outcrops that extends between Shabicha and Nisab (Ansab), where travel by vehicles is extremely difficult. In this region Ad Dibdibba morphology gives way to a topography which is controlled by a series of scarps that radiate around a point just to the south of the Iraq-Saudi Arabia Neutral Zone. These scarps and alignments, of variable form and size, are from east to west as follows: Al Busayyah, At Traq, At Takhadid, Al Wqisah (Wagsa), Al Qasas, and Al Batn. Each scarp line passing northward takes on a general north-northwest trend extending toward Wadi Al Ghadaf, north of the area. The scarps coincide with different beds of the Damman and Umm er Radhuma Formations. Their general distribution can clearly be appreciated from the geologic map (pl. 1). In the Hajara region there are a number of broad depressions which form internal drainage systems.

Westward from the Euphrates Limestone Formation, the outcrops are almost flat. The topography changes in the area of Damman limestones. The main feature in the southern part, beginning north of Alm Ghanzir (lat 30° 17' N., long 45° 25' E.), is the big scarp of At Traq, trending generally southward; local embayments face towards the east (for example, Faydat az Zahra, near Shibrumiya, Ad Dayir). Near Khashmat al Muharh, the trend of the scarp swings due east, toward Tuqaiyid, and from there it again trends southward and then disappears east of the north tip of the Neutral Zone. The difference in altitude between the scarp and the low-lying ground west of it is as much as 50 meters.

West of At Traq, a higher ridge trends north-northwest. Toward the north it disappears in the vicinity of Zum, and in the south it plunges underneath the Dibdibba Formation. Another prominent feature is Chabid (Kabid), which is a flat-topped hill farther west, rising 38 meters above the surrounding low-lying country and characterized by the steep cliffs which delimit it. Some distance west of this is another scarp that trends north-northwest.

Still farther west, there are two dominant topographic features: the Wagsa-Jil Raschid scarp and the Al Batn scarp. Both are aligned roughly north-northwest and face westward, forming three distinct parallel strips or zones, which are gently tilted to the north-east. The most easterly zone extends from Nisab (Ansab) to Ash Shabakah (Shabicha), and then to the west edge of the very rocky area known as Al Hajara. The second strip, between the Batn and Wagsa scarps, is named Al Basita; this is also rocky in parts, but is

not marked by any very distinct drainage system. The zone below the Batn scarp, known locally as Hamrat al Batn, is more dissected than the Basita area; its drainage is poorly defined, and the terrain is dotted with numerous small depressions, each having its own catchment.

Farther north, all these scarps and features tend to lose their distinctive characteristics. West and south-west of An Najaf and Karbala the area becomes rather tabular. Hills (mesas) capped by silicified limestone, occur in the eastern belt and are generally small, being some 10-20 meters above the plain or wadi floor. Old wadis, dating from pre-Zahra or even pre-Fars times, cut only slightly into the stratigraphic succession and reveal minor scarps from time to time, although collapse structures, slumping, and bending of beds generally smooth out the morphology.

Two major scarps dominate the topography of this part of the region: The first of these is the Upper Fars scarp, which forms the first major scarp on the west side of the Mesopotamian structural valley. Its average height is 50 meters; it has a roughly northward trend; and it extends far beyond the limits of the area considered. The second is the Batn az Zawr scarp, which like the Upper Fars scarp is due to differential erosion of regionally tilted rocks. Near the top of the Damman chalks is a bed of chert, 0.5 meter thick, so competent and resistant to erosion that it virtually controls the steep scarp face which extends for a long distance, and it can be considered as the extension of the Wagsa scarp. This scarp forms the eastern boundary of an extensive Miocene Zahra-Euphrates embayment of deposition that transgressed over all formations in the area, from Miocene to Cretaceous. Erosion of these later sedimentary rocks is responsible for the varied irregular hummock and plain topography of the broad area to the south of Nukayb (Nukhaib).

A number of wadis, including Wadi Arar, Wadi Hamir, and Safawiyat (Shaib) Al Ubaydat, which have their origin in Saudi Arabia drain into gentle depressions south of Nukhayb, such as Khabra al Qatah and Faydat al Adyan.

In the extreme southwestern part of Al Hajara, north of Al Busayyah toward Abu Ghar, the Euphrates limestones form numerous isolated hills, especially in the region of Al Afaif. The Lower Fars Formation, which occurs between the Euphrates limestones and Dibdibba beds, generally forms a pronounced ridge. The drainage here flows toward the north into the sand-dune belt on the west bank of the Euphrates River. The principal intermittent water courses are the Shaib Abu Ghar with its tributaries, Shaib Juda and Shaib Luwaihadh. Some distance farther west,

Shaib Sudayr drains a big part of the territory covered by Tuqaiyid limestone, which underlies the Euphrates Limestone Formation. The drainage system in the western desert is characteristically subdivided between those shaibs which drain into the Euphrates River and those with interior drainage into inland depressions, mudflats, and lakes.

The Tuqaiyid, Barbak, and Ghanimi sedimentary-rock units extend north-northwestward from the Al Busayyah area toward al Khirr, where they overlie the Euphrates limestone. The regions covered by these units are generally flat, the dip and slope commonly toward the northeast. The drainage lines have the same trend. These include Shaib al Ghanimi, with its tributaries Shaib al Arjawi and Shaib Abu Finajin, Shaib Ashali, Shaib al Haisam, Rijlat As Salhubiya, Shaib Firk (Firch), Shaib Huwaymi, Shaib Hish, and Wadi Al Khirr. Most of these lead northeastward to the mudflats and sabkhas bordering the Euphrates River.

Beyond An Najaf, the drainage from the desert is interrupted by the long Upper Fars sandstone ridge of Al Lisan Tar as Sayyid, which trends northward from Tuqtuqaah. The presence of this ridge has given rise to the salt lakes of Bahr Al Millh, which lie east of Shithatha.

Numerous wadis that cross the area from west to east drain into these salt lakes, following a general easterly direction. These include the Wadi al Ubaiyih and Wadi al Ghadaf, which have their origin in Saudi Arabia to the west. In the central parts of Al Hajara there are several depressions into which numerous wadis drain in the rainy season. The Ghanimi depression, which is drained by Shaib al Ghanimi, forms a conspicuous inland drainage system southwest of Al Qusayr. To the south of Ghanimi, the drainage flows mostly into a number of isolated systems each emptying into a depression with no outlet, such as Jahama, Tukayyid, and Faydat as Zahra. Farther west, in the neighborhood of As Salman, there is a group of very deep depressions completely surrounded by cliffs, some of which have a relief of as much as 50 meters. These have no surface outlet, owing to the flatness of the country, and form several topographic closed basins of varying diameter, which may be as much as 15 kilometers. Extensive pools form in some of these depressions after rains. Northwest of this area, the vicinity of Ash Shabakah (Shabicha) and Barabir is marked by a few important depressions. Several solution holes, such as Ashuriyah and Chebritiyah, occur in the area.

AL WIDYAN COUNTRY

Al Widyana area, within the study region considered, includes outcrops of the Umm er Radhuma, Tayarat,

and M'sad Limestones west of the Zahra and Euphrates limits. The topography is more undulating westward, beyond the Tertiary-Cretaceous contact. The country is deeply dissected, with broad, deeply incised wadis, many more than 1 kilometer across, bounded by steep scree-covered and slumped walls attaining altitudes of 40-50 meters. The eastern part of the area is drained chiefly by the Wadi al Ubayyid and its tributaries Wadi Tibaland and Wadi al Mira and by the Wadi al Ghadaf and its tributaries, which all flow generally eastward, ultimately ending in the Bahr al Milh, west of Karbala. The western part of this area is drained by Wadi al Hauran, which flows northeastward. Within this catchment several solution holes of various sizes are irregularly distributed and are limited mostly to the Paleocene beds. These include Wadi al Ghadaf (E. 1188, N. 1195), Jelta (E. 202, N. 1173), Kursa (E. 225, N. 1160), and Wishwashia. Al Umchaimin, in the Al Hamand plain, to the west of the area, is a similar feature (Merriam and Holwerda, 1957).

The origin and mode of formation of these solution holes may vary widely, and some may be attributed to the combined effect of several different mechanisms. For example, for the Al Umchaimin, which is a large depression, Merriam and Holwerda (1957) postulated meteoritic origin, whereas Mitchell (1958) argued for a possible volcanic origin. The majority of the geologists of the Basrah Petroleum Company, however, considered it best explained in a less dramatic manner. They maintained that the initial dissolution probably began along fracture surfaces and so lead to the development of a rudimentary underground drainage pattern. Evidence of this pattern remains in the small tunnels now partly blocked by collapse debris. The vertical drainage through fractures then apparently augmented the underground streams and swallow holes were formed. This stage is possibly represented by holes at Kursa and Wishwashia. Continued dissolution finally resulted in the foundering of the roof and in the formation of a large collapse structure of irregular outline, as at Jelta and Wadi al Ghadaf. Theoretically it would seem that this kind of topographic feature can originate in different ways: the effect of climate on geological structures and rock facies, volcanic activity, or meteoritic impact.

STRATIGRAPHY

GENERAL FEATURES

PHILOSOPHY OF NOMENCLATURE

The incompleteness of the geological record is not peculiar to the systems in Iraq. Establishment of the stratigraphic sequence in virgin territory depends pri-

marily on the background of the investigators and the amount and type of data available. Through the efforts of a great many geologists of the Iraq Petroleum Company and its associated companies, a great mass of geologic, stratigraphic, and paleontologic information and material has been accumulated. After 33 years of investigation the progressive synthesis had reached a stage, toward the end of the last decade, at which the broad patterns of the sedimentation in Iraq were fairly well established. A statement of the stratigraphic synthesis was published by Dunnington, Wetzel and Morton for Paleozoic and Mesozoic units and by Bellen for Tertiary units (Bellen and others, 1959) in the Stratigraphical Lexicon for Iraq sponsored by the Commission on Stratigraphy, International Geological Congress.

The system of rock-unit classification and naming employed by Iraq Petroleum Company geologists is advocated in the code of rules compiled by Ashley and others (1939) as supplemented in recent papers and rulings of the Commission on Stratigraphy.

It has been generally realized that the sedimentation realms were dominated by the proximity of the Arabian shield on one side and by the Zagros (Tethys) geosyncline on the other and that the sedimentary characteristics followed the natural shore-to-basin pattern from the Arabian shield east and northeastward. Furthermore, the sedimentary patterns showed clear diachronism following epeirogenic cycles in western and central Iraq and diastrophic and orogenic movements in northern and northeast Iraq. Of course, an attempt has also been made to define the basic units of the sedimentary cycles. However, because of gaps in knowledge and especially because of paucity of information on the deep subsurface stratigraphy of central Iraq, separate stratigraphic nomenclatures were developed for northern and southern Iraq.

Description of some of the rock units of southwestern Iraq was published by Owen and Nasr (1958), and all the formations except for the newly defined Safawi and lately defined Kifl Formations were redescribed and expanded by Bellen, Dunnington, Wetzel, and Morton (1959).

The present report is chiefly based on the above works, supplemented by later unpublished works of a number of geologists, including especially M. C. Chatton and E. Hart. Some of the original descriptions of individual formations have been revised, redescribed, and expanded, where necessary, to take into account the findings of recent investigations and especially of recent deep wells in the southern and western areas.

TIME UNITS REPRESENTED

In western Iraq the oldest rocks exposed, the Nijili Formation and the overlying Ga'ara Sandstone Formation, are of Middle Triassic age; the Ga'ara is followed unconformably by the Upper Triassic Mulussa Formation, which is succeeded upward by the Rhaetic (?) Zor Hauran Formation and the Liassic (pre-Toarcian) Uba'id Formation. The Bathonian-Bajocian Muhaiwir Formation overlies the Uba'id Formation with probable unconformity. A major unconformity exists between the Middle Jurassic Muhaiwir and the overlying Middle Cretaceous Rutbah Sandstone. All the Middle Triassic, Jurassic, and Lower and middle Cretaceous units are exposed in the Ga'ara depression and Wadi Hauran, which are to the north of the area of review. No detailed account will therefore be given of them.

In the area of present consideration, the exposed rocks range in age through middle and late Cretaceous, Paleocene, Eocene, Miocene, and Pliocene Epochs to Pleistocene and Recent. With the exception of the Al Hamad plain in the extreme western part of Iraq, where the Cretaceous units are succeeded westward by Paleocene formations, the general sequence of the exposed formations is in ascending stratigraphic order to the east. The Oligocene Epoch is not represented by any rock unit in the area, owing to the great unconformity between the Eocene and Miocene Epochs, though there was some tendency in the past to assign an Oligocene age to the Tuqiyid beds of the Dammam Formation.

In the subsurface sections of the area, the oldest sequence found is the Butmah Formation in the BPC (Basrah Petroleum Company) well Samawa No. 1, which was completed at a total depth of 12,602 feet. This formation is Early Jurassic in age.

GENERAL DISTRIBUTION OF SYSTEMS AND DOMINANT ROCK TYPES

The surface occurrences of the different systems and their general areal distribution in the defined area are illustrated on the geological map (pl. 1). This map shows the presence of a major stratigraphic gap between the Bathonian and Bajocian Muhaiwir Formations, and the overlying Cenomanian Rutbah Sandstone Formation in the Ga'ara area, a little to the north of the area that is considered in detail. This hiatus becomes less important away from the Ga'ara-Khaleisa high. The sequence is almost complete in the wells of the Basrah area, but there are successive convergences northwestward, beneath the pre-Cenomanian unconformity. Thus the Cretaceous System is only partly represented in outcrop, the oldest exposed rock

units being the Cenomanian and lower Turonian Rutbah Sandstone and M'sad (Mishrif) Limestone, which come to the surface only in the region of the Ga'ara depression, especially in the Wadi Al Hauran area.

The Upper Cretaceous (upper Campanian and Maestrichtian) is represented by the Tayarat limestones, which include subsidiary marls and thin shales. They cover most of the Al Widiyan region, where between the Upper Cretaceous and middle Cretaceous (Cenomanian) there is an extensive hiatus. The missing rock units include those of the middle Turonian and lower Campanian cycle, which are widespread in the subsurface in the eastern parts of the region. These rocks include the basinal Khasib limestones, neritic Tanuma shales, and Sadi subbasinal chalks and limestones. Also, the upper Campanian Hartha limestones and the related Safawi evaporites, which are well represented in the subsurface section in western Iraqi wells, wedge out between the westernmost well and the outcrop belt.

The Paleocene series embraces the Umm er Radhuma Formation, which consists of two main limestone units in the surface exposures. These trend north-northwestward along the western Iraqi-Saudi Arabian border. In the Al Widiyan area the Umm er Radhuma limestones are exposed both east and west of the Cretaceous outcrops. The Umm er Radhuma is very extensive in the subsurface beneath the western desert.

The overlying Eocene Dammam limestones crop out along parallel belts that are also oriented north-northwestward. These limestones also have a widespread subsurface distribution in the area. The evaporitic Rus Formation is present in the Basrah area as a lateral facies variant at the base of the Dammam.

The Oligocene series is not represented in the area.

The relations of the rock units of the Miocene series are complex. The lower Miocene is perhaps represented by the Euphrates Limestone, which crops out along the east margin of the area and in the Al Busayyah region. The stratigraphic position of the Zahra beds is rather problematical, but they are generally included in the Miocene. They occupy old depressions and wadi floors, occurring as isolated outcrops in the southern and central areas and as extensive sheets in the northern and western parts of the area where they overlie rocks of both Paleocene and Eocene ages. The middle Miocene Lower Fars evaporites cover the Basrah area and follow the general distribution of the Euphrates Limestone. The Lower Fars evaporites are underlain by the clastics of the Ghar Formation, the relationship between the two rock units being one of facies change by intergradation, the incidence of evaporitic components diminishing westward.

In the north the Lower Fars evaporites are succeeded by Upper Fars sandstones and siltstones in the region of Karbala, where they underlie the Recent Mesopotamian alluvium, whereas in the south the Lower Fars is directly followed by the rudites of the Dibdibba Formation, which covers the Dibdibba physiographic region of southern Iraq. In the Basrah area the Dibdibba Formation dips under the Recent marine sediments and alluvium of the Hammar Formation.

The 27 formations recognized in the area are described below, in ascending stratigraphic order, beginning with the Lower Cretaceous Ratawi Formation. The relations of these units to each other and to correlative units in other areas are illustrated on plate 2.

The schematized regional correlation of the current rock units (pl. 2) is based on plates 4 and 6 in Bellen, Dunnington, Wetzel, and Morton (1959), or work by Naqib (1960), and on unpublished diagrams by M. Chatton, E. Hart, and the writer. It illustrates the general horizontal and vertical distribution of the different rock units in broad terms and their relation to counterparts in Arabia. A broad and general tentative subsurface stratigraphic correlation of the rock units in the area is shown on plate 3.

UNCONFORMITIES

The geological column of Iraq contains numerous erosional and nondepositional hiatuses. Most of the unconformities which are recognized and accorded importance in the area are disconformities in which two units of stratified rock are parallel but separated by an erosion surface having appreciable relief. Discernible angular discordance is very rare, except for localized and surficial unconformities of the Zahra beds on irregular topography in the western and southern desert areas. Some of the major disconformities involve very considerable convergences, with progressive cutout of hundreds or thousands of feet of sediments, but the distances over which the convergences are distributed are so large that the angularity is not visible.

In Iraq the geological sequence, from Triassic time to possibly late Miocene, consists of units that preserve their general characteristics over large regions in which the more significant variations are related to paleogeographical position within a basin. The recognizable erosional unconformities relate to epirogenic movements.

According to Dunnington, Wetzel, and Morton (Bellen and others, 1959), the Upper Triassic (Mulussa Formation) is unconformable on the Middle Triassic (Ga'ara Sandstone). Though there is no apparent angular discordance or convergence, there is a well-

marked erosional surface indicating subaerial exposure at the top of the Ga'ara Sandstone.

Only one major unconformity of any significant regional extent has been detected in the Jurassic succession, this being the well-marked break between the Middle Jurassic and Upper Jurassic. There is no recognizable unconformity or sedimentary break at the Cretaceous-Jurassic boundary. According to Dunnington, Wetzel, and Morton (in Bellen and others, 1959), the subsurface sections, especially in the north, show an erosional unconformity lying within the Berriasian, though unpublished work by E. Hart and M. C. Chatton has cast doubt on the existence of this break.

The Cretaceous sequence is divided by a number of widespread unconformities of Albian-Aptian, Cenomanian-Albian, Turonian-Cenomanian, and upper Campanian-lower Campanian ages. Near the area of review the most spectacular of these is the onlap of the Cenomanian over eroded extremities of units as old as Middle Triassic. The Cretaceous rock succession terminates at a widespread major erosional unconformity (disconformity) of post-Maestrichtian (or very late Maestrichtian) date, which is followed by Paleocene or younger sediments, the Danian being unrepresented.

The unconformities in the Paleocene and Eocene succession may be of paraconformity type. The most important gap recognized is between the transgressive Eocene (Dammam Formation) and Paleocene (?) and Lower (?) Eocene (Umm er Radhuma Formation).

A major discontinuity exists between the Eocene units and the overlying Miocene sequence, the Oligocene being unrepresented throughout the entire area of study. The southwestern shoreline of the Oligocene sea lay to the northeast of the Euphrates, and the Eocene rock units were subaerially exposed over the whole area through Oligocene time.

In the Miocene and Pliocene succession, unconformities on both large and small scales can be detected. These include the disconformity between the middle Miocene (Lower Fars) and lower Miocene (Euphrates Limestone), the disconformity between the Pliocene (Dibdibba Formation) and middle Miocene (Lower Fars), and the commonly angular unconformity of the Zahra beds on the underlying older rocks, as well as paraconformities and diastems within each of the main units. Finally, the Dibdibba Formation is unconformably overlain by the Recent Hammar Formation.

The present-day erosion surface exposes a sequence ranging from Triassic to Recent. The topography on the whole is flat with gentle east-northeasterly dip and slope. Intermittent wadis cross the region in this general slope direction. Interior drainage basins and depressions locally interrupt the general pattern, which

is largely dictated by the dip slopes and strike escarpments of the almost flat-lying sedimentary sequence.

REGIONAL SEDIMENTARY PATTERN AND HISTORY

The individual formations from the surface and subsurface type or reference sections have been treated independently in some detail elsewhere, but in any stratigraphic work it is not sufficient to describe specific rock types or individual sedimentary environments without discerning the broader sedimentary patterns. The reconstruction of these patterns is primarily based on good correlation by fossil content (biostratigraphic units) but also on equivalences in lithology (rock units). Thus a pattern advanced today may later be modified or completely altered in the light of new evidence that leads to a completely different history and picture. With proper correlation and the knowledge of mode of sedimentation, it may be possible to reach a reasonable pattern which could convey the actual history of sedimentation in time and space. The pattern presented here is, of course, subject to the validity of the correlation and to a proper assessment of the mode of sedimentation and modifications introduced during subsequent geological history.

Southwestern Iraq occupies a position between the relatively stable Arabian shield in the west and the highly mobile Zagros belt in the east. The Zagros mountain belt has risen on the site of the great "Tethys geosyncline" which persisted from at least Permian until middle Miocene time.

In this work only the period from Early Cretaceous to Recent is treated because the present information on older rocks in the area is scanty. The Cretaceous to Recent stratigraphic sequence is similar to rocks normally found on stable continental platforms. It is made up of units that are rather widespread. Facies changes are not unusual, but they are generally gradual. The type of sedimentary rocks and erosional unconformities in the successive geological periods indicate that the area was the scene of periodic epeirogenic movements; some tectonism, as evinced by broad swells, depressions, and perhaps block faulting, accompanied regression and transgression of the seas. The western shorelines during these geological periods followed the margins of the Arabian shield, the axis of the basin or geosyncline being far away to the east in western Iran and eastern Iraq. The effects of geosynclinal depositional conditions upon sedimentation in the platform region must have been very small. The Arabian shield, and to a lesser extent the Ga'ara-Khleisa high, must have been the primary source of the sediment that was deposited over western Iraq. In recent unpublished work on the region, great stress has been put on the

importance of diachronism as a factor controlling the sedimentary pattern. Dunnington (1958) and Dunnington, Wetzel, and Morton (in Bellen and others, 1959) recognized the prevalence of diachronous contacts of many of the Mesozoic rock units, and Bellen (1956; Bellen and others, 1959) dealt in some detail with the age relationships of facies-dictated Tertiary rock units in which diachronous lateral passage is a characteristic feature. Lately, M. C. Clifton and E. Hart, in as yet unpublished studies, have endeavored to simplify the correlation problems between northern and southern Iraq by recognizing a more extensive contribution of diachronism of rock facies to the sedimentary pattern. Their work affects chiefly the Cretaceous sedimentation cycles, which are briefly defined as follows:

1. Tithonian (Upper Jurassic) to Aptian cycle includes the following formations, in order, from the shore to the center of the basin: Zubair, Ratawi, Yanama, Qamchuqa, Sarmord, Chia Gara, and Balambo.
2. Albian cycle includes the following formations from shore to basin: Burgan, Nahr Umr, Nahr Umr Shales, Qamchuqa, and Balambo.
3. Cenomanian to lower Turonian cycle includes the following basic formations from shore to basin: Rutbah Sandstone, Admadi, Mishrif, Rumaila, Dokan, and Balambo. The Kif Formation is considered as the lagoonal-evaporitic facies on the shelf at the terminal phase of the cycle.
4. Middle Turonian to lower Campanian cycle includes the following basic recognized formations from shelf to basin: Khasib, Tanuma, Sa'di, Kommetan, and Balambo.
5. Upper Campanian to Maestrichtian cycle includes the following formations from shelf to basin: Safawi, Hartha and Tayarat, Shiranish, and Tanagero. The Bekhme and Aqra Limestones may be considered to be the respective equivalents of the Hartha and Tayarat Formations in northern Iraq.

The Tertiary group of sediments in Iraq follows broadly similar sedimentary patterns; however, owing to lack of adequate information the general picture seems rather confused for the Miocene and Pliocene series. The main cycles follow.

1. Paleocene cycle may extend into the lower Eocene. The main formations composing this cycle from shelf to basin include: Upper Radhuma, Anlaji, Sinjar, Khurmala, and Kolosh.
2. Eocene cycle is chiefly confined to the middle and upper Eocene, and it includes the following for-

- mations from shelf to basin: Dammam, Rus, Jad-dala, Avanah, Pila Spi, and Gercus (red beds).
3. Oligocene cycles are characterized by three reef-controlled cycles that are recognizable in central and northern Iraq; however, they have not been found in southwestern Iraq.
 4. Miocene cycles:
 - a. Lower Miocene cycle(s) may be more than two cycles. An older cycle includes the Euphrates Limestone, Dhiban Anhydrite, and Sevikagni Formations. A second cycle includes the Jeribe Limestone.
 - b. Middle Miocene cycles include the evaporitic Lower Fars sequence and Ghar Formation. The Zahra Formation is problematical and difficult to include in any of the recognized cycles with any certainty. There may be many cycles, as evidenced by the rhythms of the Lower Fars sediments, particularly in the region of full thickness in northern and eastern Iraq.
 5. Pliocene and Pleistocene cycles: The Dibdibba, Bakhtiari, Upper Fars, and Lower Fars Formations. These formations certainly represent more than one cycle, but lateral and vertical relationships remain somewhat obscure.

The above Mesozoic and Tertiary and Quaternary cycles constitute merely the main patterns of sedimentation over the whole of Iraq. These broad patterns, however, should not rule out the possibility of minor patterns due to localized cycles, or local movements and environments. Indeed, local divergences from this simple pattern are by no means rare: many minor cycles do in fact occur within the major cycles, sometimes perhaps to the extent of obscuring the broad and generalized (and therefore somewhat oversimplified) outline.

In the general sedimentary province, southwestern Iraq lay in the shelf zone from Triassic to Recent time. During this long interval the area underwent a series of periodic epeirogenic movements with fluctuating intensities which resulted in periodic emergence or submergence of the land. Thus almost all the sedimentary rocks that occupy the area have characteristics of the shelf facies. For a general understanding of the sedimentary history, brief recourse is made to the older outcrop systems of the Ga'ara area.

During Triassic time the sea covered most of the area; its shorelines must have been not far west of the Ga'ara, as (according to Dunnigton, 1958) the clastics of the lower parts of the Nijili show continental features. During Middle Triassic time the Nijili saliferous marls and shales and their overlying Ga'ara sand-

stones and quartzites were deposited. These were succeeded unconformably, though without angular discordance, by the Upper Triassic Mulussa limestones.

These were subsequently covered by the Rhaetic Zor Hauran gypsiferous marls, shales, and marly or oolitic limestones and by the dolomitized and recrystallized Liassic Uba'id limestones, which were succeeded by alternations of limestones and evaporites, indicating intermittent barred-basin conditions during Liassic time. This alternating evaporite sequence is represented in the Butmah shales and limestones, Adaiyah anhydrites, Mus limestones, and Alan anhydrites. The Liassic sequence has not yet been recognized in outcrop, though it is well developed in subsurface sections in the area, as in Samawa well No. 1. According to Dunnigton, Wetzel, and Morton (in Bellen and others, 1959), however, it is possible that Liassic equivalents do occur at outcrops in the Wadi Hauran area. Toward the basin, during Bajocian and Bathonian times, bituminous black limestones, dolomites, and shales of the Sargelu Formation were laid down; westward, however, the neritic Muhaiwir limestones of the Ga'ara area were deposited. The Middle Jurassic sedimentation was terminated by a major regional unconformity (Bellen and others, 1959). During Late Jurassic time, as a result of a marine transgression cycle over the area, the Najmah limestones and Gotnia evaporites were deposited. Later they were succeeded by the shallow-water Upper Jurassic and Lower Cretaceous Sulaiy Formation.

According to M. Chatton (unpub. data, 1960), sedimentation during the Tithonian-Aptian cycle was continuous, but involved a single major regression and transgression of the sea. It seems that Yamama calcarenites and oolitic limestones were first deposited on Sarmord-type sediments (as in wells Samawa No.1 and Kifl No.1) with which they intergrade. The overlying Ratawi neritic shales and limestones (with subordinate sandstones, Zubair sands, neritic shales, and subordinate limestones) were being deposited contemporaneously in their respective belts of sedimentation. The oscillatory migrations of the belts are distinctly observable in the ratios of sand to shale components that make up the Zubair Formation, and apparent overlap of one formation on the other may be best interpreted as being due to diachronism. The Shu'aiba limestones represent the rapid transgression of the sea at the close of the cycle. In most localities shales similar to the Ratawi were deposited between the Zubair sands proper and the Shu'aiba limestone.

During Albian time, after a brief period of emergence evidenced in the unconformity between the Nahr Umr Formation and the Shu'aiba Formation, the Bur-

gan sands and Nahr Umr shales and sands were deposited during a transgressive-regressive phase, which was followed by a rapid Maaddud transgression. The Maaddud neritic limestone sedimentation ended with epeirogenic withdrawal and emergence.

The Cenomanian cycle followed the same general pattern, with the additional complication that some kind of high must have formed to account for the growth and deposition of the Mishrif bioherms and biostromes in the Basra area. These are distributed in an arcuate belt, trending north-northwest. As might be expected, the sediments on the two sides of the biohermal belt are different.

In the Ga'ara area the Cenomanian cycle is represented by the Rutbah sandstones, whereas in Kuwait and southern Iraq the corresponding sedimentary sequence comprises the thin sandy Wara Formation, followed by a thick sequence of rock units comprising in turn the neritic shales and marls of the Ahmadi Formation, subsbasinal Rumaila chalks and limestone, and Mishrif neritic limestones. The cycle was terminated locally by the deposition of the lagoonal evaporitic Kifl Formation. This indicates that an enclosed basin covered the western part of the region during latest Cenomanian and (perhaps) early Turonian times.

Clastic and neritic limestone sediments of the middle Turonian and lower Campanian cycle limestones are not recognized in the area. The Khasib subsbasinal limestones, the Tanuma neritic shales, and the Sa'di basinal chalky limestone are represented in the eastern subsurface sections only. This may indicate that the sea during this period had transgressed over such a large area that the clastic components could not reach the region. The greatest recognized thickness of the Khasib, Tanuma, and Sa'di Formations is found in the Rumaila-Rachi area. It may be that the sand and neritic limestone sedimentation belts of the Turonian and lower Campanian cycle may lie as yet unknown in the area between the westernmost subsurface sections (Ghalaisan well No.1, Samawa well No.1) and the easternmost outcrops (Wadi Hauran and Rutbah areas).

Some indications of the imposition of a new tectonic framework within the depositional basin are apparent in the sediments of the Turonian and lower Campanian cycle. During the succeeding upper Campanian and Maestrichtian cycle, this framework was firmly established. A major uplift of the Middle Cretaceous and older basinal sediments occurred on the site of the present Zagros mountain belt northeast of the area of study, and a deep trough, trending northwest, sank at the foot of this uplift to accommodate vast volumes

of flyschlike clastics derived from the newly emerged highlands. At the same time major east-west troughs formed in the Sinjar area of northwestern Iraq and northeastern Syria and at Anah, on the Euphrates River, north of the Ga'ara high. In the Basrah area some warping of the platform on east-west swells and troughs is evidenced in the thickness and facies distribution of the Upper Cretaceous rock units.

These rock units fall into two subcycles, or phases, in southwestern Iraq. The lower subcycle consists largely of the neritic limestones and shales of the Hartha Formation, with its newly recognized evaporitic lagoonal equivalent, the Safawi Formation. The upper subcycle was inaugurated by widespread deposition of globigerinal marls, formerly named the Qurna Formation but now identified with the Shiranish Formation of northern Iraq. It terminated with the deposition of the neritic Tayarat limestone over the whole area.

The energetic tectonism of northeastern Iraq at this time was apparently in the south and west. The relations of the rock units here imply that toward the close of the Hartha sedimentation came a period of quiescence; and in the extreme west, lagoonal basins formed, as evinced by the Safawi Formation. The subsequent deposition of Shiranish marls implies deepening, but there may be a minor unconformity between the two phases. The second phase, wherein the basinal Shiranish marls were deposited over much of the area (except for the extreme west where Tayarat limestones were being laid down), was manifestly transgressive. Toward the end of the Maestrichtian, the area apparently underwent a regressive period whereby the neritic Tayarat limestones migrated eastward in the wake of the Shiranish belt of sedimentation. This cycle was terminated by the major Cretaceous-Tertiary unconformity.

The Cretaceous-Paleocene transition period was one of widespread regression, which exposed most if not all of the region, resulting in a major and extensive unconformity, after which sedimentation recommenced with the deposition of neritic and lagoonal Umm er Radhuma limestones (Paleocene and lower Eocene?) over most of the area.

Bellen (Bellen and others, 1959) state that the proximity of the Ga'ara high resulted in a garland of neritic reef and shoal deposits (the Umm er Radhuma Formation) east of it. This facies has been found to extend to Kifl well No.1, to cover almost the entire area of discussion, and to extend west and southwestward into Saudi Arabia, where the proximity of the Arabian shield has been the deciding factor in the mode of sedimentation of this cycle. In the transi-

tion belt the neritic shoal facies of Umm er Radhuma pass eastward, with intergradation, into basinal Aaliiji marls and marly limestones. There is also strong evidence for shallowing of the sea and gradual northeasterly retreat, resulting in the migration of the neritic facies line toward the basin.

This regression was followed by a gradual advance of the sea that permitted the formation of semibarred restricted basins in which the evaporitic Rus Formation was deposited in the central and southern parts of the area during early stages of the early Eocene sedimentation. Good evidence of this marine advance exists in the relationship of the open sea basinal sediments of Aaliiji and the overlying Rus evaporites in the Kifl region. Northward the neritic Damman Formation passes into the basinal Jaddala Formation.

The Eocene cycle was terminated by a period of uplift during which the uppermost part of the Damman Formation was eroded over an extensive area, including parts of the Arabian Peninsula. Bellen (1959) stated that after the deposition of the Eocene a regression of some importance occurred, followed by a transgression of smaller extent, introducing the first Oligocene cycle.

Three Oligocene cycles are recognized in northern and central Iraq where the sedimentation was controlled by immigrating and emigrating organic reefs (Bellen, 1956) back reef, reef, fore reef, and basinal sediments: (1) Anah Limestone, Azkand Limestone, and Ibrahim Formation, (2) Bajawan Limestone, Baba Limestone, and Tarjil Formation, and (3) Shurau Limestone, Sheikh Alas Limestone, and Palani Formation.

The Oligocene series has not been recognized in outcrops nor in subsurface sections in the area including the Afaq well No.1 area. However, there are occurrences of back-reef and reef Shurau in Awasil well No.5: the back-reef and reef Shurau Limestone, the back-reef and reef Bajawan Limestone, and fore-reef Baba Limestone in Falluja well No.1; the basinal Palani, fore-reef Sheikh Alas, back-reef and reef limestone of the Shurau, fore-reef Baba Limestone, and Bajawan back-reef and reef in Musaiyib well No.1; and the basinal Palani and Tarjil, fore-reef Baba Limestone, and back-reef and reef Bajawan Limestone in Dujailla.

These widely scattered occurrences suggest that back-reef and reef Shurau of the first cycles trended northwestward from the area of Awasil well No.5 to Musaiyib well No.1 and Dujailla well No.1 in an arcuate belt and that the lithological belts of the three superimposed cycles apparently shifted repeatedly

basinward. Although it may be possible to visualize the present westerly limits of these cycles, their original extent cannot be detected because the Ogliocene Series is absent in southern Iraq, probably removed by erosion during a period of emergence prior to Miocene transgression.

The Miocene transgression resulted in the deposition of the Euphrates Limestone Formation over a wide area presently covering the northern and eastern parts of the study region. The Ghar clastics suggest that it belongs to this early cycle and forms the near-shore deposits; this attribution is, however, arguable. The evaporitic (Dhiban) equivalent of the Euphrates was found in Musaiyib No.1, northeast of the area. This evaporitic unit succeeded the Euphrates Limestone and according to Bellen (Bellen and others, 1959), was precipitated from sea water after the access to the sea arm, probably in the south, became wholly or partly closed.

This cycle was succeeded by the transgressive Jeribe limestones which have been found in wells Awasil No.5, Fallujah No.1, Kifl No. 1, Musaiyib No.1, and Afaq No.1. The transgression may have reopened access to the gulf, a condition that may have brought the evaporitic precipitation to an end and introduced lagoonal sedimentation once again. It is difficult to determine the westerly extent of the Jeribe Limestone. Its areal distribution suggests that before the deposition of the Lower Fars evaporites there had been a short period of emergence and erosion of some of the Jeribe Limestone in the west. The position of the Zahra Formation is rather obscured by the lack of knowledge of the stratigraphic relationships of several formations.

The Lower Fars evaporites were laid down in a restricted basin in the form of a barred gulf or arm of the sea, where the sedimentation was governed by events near the exit of the gulf in which the sediment was deposited. Restriction of the basinal exit, according to Bellen (Bellen and others, 1959), caused the deposition of anhydrite and salt. Its opening resulted in limestone and in siltstone and shale sedimentation.

After the deposition of the Lower Fars, rapidly rising mountains in northeastern Iraq produced large quantities of detritus. This material was at first deposited in a marine environment and formed the clastic Upper Fars Formation of late Miocene age. Representatives of this formation are seen in the eastern part of the depositional area. Meanwhile, less clastic Middle Fars limestones and siltstones were deposited in the southern part of the depositional area. The large quantity of mountain-derived detritus rapidly forced the sea to retreat. A continental environ-

ment spread southward; and sands, sandstones, gravels, and finally thick conglomerates (the lower and upper formations of the Bakhtiari Group of Pliocene age) spread over the marine Upper and Middle Fars Formations.

In the area of the Ga'ara high, the Lower Fars Formation is missing. The western known limit of this formation lies a little to the west of the Euphrates River in the Awasil area. In the south the position of the formation is not clear. The elastic Ghar Formation may be a somewhat detrital facies of the basal beds of the Lower Fars Formation, whereas the Zahra Formation may have been deposited as lacustrine, in places *Chara*-bearing, limestone in landlocked depressions at the end of the period of Lower Fars deposition. Further fieldwork is needed to clarify the stratigraphy in this area.

In the south, land-derived detritus subsequently formed the thick Dibdibba Formation, roughly comparable in lithology to the rocks of the Bakhtiari Group of the north. Part of the Dibdibba may represent part or all of the Middle and Upper Fars Formation of northern Iraq. The Middle Fars, Upper Fars, lower part of the Bakhtiari, and upper part of the Bakhtiari are all absent from the area of the Ga'ara high. Alluvium in the form of lacustrine, estuarine, and fluvial deposits overlies the upper part of the Bakhtiari Group and the Dibdibba Formation. In the southern part of Iraq, however, a small subrecent transgression is present between the Dibdibba Formation and the alluvium. This has been recently defined as the Hammar Formation.

MESOZOIC

The Mesozoic Era is represented in western Iraq by sedimentary units of Triassic, Rhaetic, Jurassic, and Cretaceous ages, though there are several important gaps in the geological sequence. Triassic and Jurassic units crop out in the Ga'ara area, which lies slightly beyond the study region. Jurassic units have been found in some deep wells in the area, but information on pre-Cretaceous units is generally scanty. Descriptions of the formations are therefore confined to Cretaceous and post-Cretaceous units.

CRETACEOUS

Of the 43 established rock units of the Cretaceous period in Iraq, 18 occur in southwestern Iraq; surface and subsurface sections of these units are described in some detail. The general time gaps in the geological history of the Cretaceous Period have been dealt with in the section on "Unconformities." The Cretaceous sedimentary rocks are as much as 10,000 feet thick.

RATAWI FORMATION

TYPE SECTION, THICKNESS, AND EXTENT

The type section of the Ratawi Formation in BPC well Ratawi No.1 (lat 30°33'22" N., long 47°05'45" E.; alt 107.9 ft.; completed Mar. 18, 1950). The formation lies between drilled depths of 10,570 and 11,585 feet (715 ft thick) and takes its name from this well. It is not exposed in the western desert but is found in BPC wells Nahr Umr No. 3, Zubair Nos. 24, 38, and others; Rumaila No. 4; Samawa No. 1; Ghalaisan No. 1; and Safawi No. 1. It is also found in Kuwait, in the Kuwait Oil Co. wells Burgan No. 113, Magwa No. 1, and Umm Gudair No. 1. This formation decreases in thickness northward and westward, mainly owing to a change of facies; thickness in wells Samawa No. 1, Ghalaisan No. 1, and Safawi No. 1 are 285, 219, and 146 feet, respectively.

DETAILED LITHOLOGIC DESCRIPTION

The Ratawi Formation consists of greenish-black shales that are slightly pyritic, massive in the upper part, interbedded in the lower part, and contain stringers and beds of buff pyritic pseudo-collitic detrital fossiliferous limestones. The upper shaly beds contain some fine quartz silt.

The Ratawi Formation becomes thinner and less shaly to the northwest, for example, in Samawa well No. 1 where it is divisible into three units:

	Thickness (feet)
3. Limestone, compact, slightly porous, dolomitized, detrital, and dolomite with thin shale intercalations ...	20
2. Sandstone, porous, fine-grained, calcite-cemented, interbedded with thin shales and sandy dolomites ...	40
1. Limestone, generally tight, finely detrital, commonly characterised by pyritic mud rimming the constituent fragments; locally silty and argillaceous ...	216

At Ghalaisan well No.1 the sequence is dominantly calcareous. It comprises 219 feet of buff pyritic fine-grained limestones some of which are leached and vugular. Some of the limestones have a chalky matrix and locally grade to buff-gray or gray indurated marls. Minor shale intercalations occur at the top of the sequence and also near the base. There is a considerable and progressive reduction in thickness westward. At Safawi well No.1 the sequence comprises 146 feet of marly gray to white indurated limestones, shelly algal limestones, and arenaceous limestones. Northward and westward this formation grades into Yamama or Garagu Formations.

DIAGNOSTIC FOSSILS

Pseudocyclammina lituus (Yokoyama), *Ostrea rectangularis* Sowerby, and *Terebratula cf. squamosa* Mantell are diagnostic of the Ratawi Formation. The

lower part of the Ratawi, containing detrital limestone intercalations, has a fauna which includes *Cyclammina greigi* Henson at the top, and *Pseudocyclammina lituus* (Yokoyama), *P. cf. lituus*, *P. cf. kelleri* Henson, *Trocholina* spp., *Cristellaria* sp., and algal, bryozoan, and stromatoporeid fragments. Macro fossils include *Exogyra sinuata* Sowerby, *Terebratulina* cf. *T. squamosa* Mantell, *Anomia* sp., *Pecten* (*Synocyclonema*) cf. *P. alpinus* Mayer, *Venus pilatina* Mayer, *Cyldindrites* sp., and *Kingena* sp., including *K. cf. Zeilleria tamarindus* (Sowerby) in Douville.

The shaly part carries locally abundant microfauna, with *Choffatella decipiens* Schlumberger, *Cyclammina* spp., *Trocholina* spp., and *Pseudocyclammina* sp., including *P. cf. lituus* (Yokoyama) and *P. cf. kelleri* Henson. Abundant *Cyclammina greigi* Henson occurs at the base of this interval.

The thin pelley limestone which marks the boundary with the overlying Zubair Formation contains abundant debris of the alga *Lithocodium aggregatum* Elliott.

In Samawa well No. 1 the formation contains *Cyclammina* sp., *Nautiloculina* sp., *Pseudocyclammina hedbergi* Mayne, *P. kelleri* Henson, *P. lituus* (Yokoyama), *Trocholina conica* (Schlumberger), *T. altispira* Henson, *T. arabica* Henson, textularids, valvulinids, algae, gastropods, and ostracodes.

AGE

The age of the Ratawi Formation is Neocomian (Owen and Nasr, 1958), probably Hauterivian and Valanginian by regional correlation (Dunnington and others, 1959). The lower part of the Ratawi is considered to be of Valanginian age, largely from correlation with the better dated Garagu Formation. The age of the upper shaly division is probably Hauterivian, on the basis of the foraminiferal assemblages. This attribution is strengthened by the presence of *Lima carteroniana* d'Orbigny in the immediately overlying Zubair Formation; this form is especially abundant in the Hauterivian of other Tethyan regions (R. G. S. Hudson, unpub. data).

CONTACTS AND EQUIVALENT UNITS IN ADJACENT AREAS

The contacts of the Ratawi Formation are easily detected on electric self-potential and resistivity logs. The base of the underlying Yamama Formation is set at the top of a thick sequence of fine-grained marly commonly pelley limestone, which has been variously treated in unpublished work by P. M. V. Rabanit, S. N. Nasr, W. Sugden, and others. The upper parts of these limestones should perhaps best be referred to the

Yamama Formation of Qatar (W. Sugden, unpub. data), and Owen and Nasr (1958) did identify them with the Yamama of Saudi Arabia.

The age equivalents of the upper shaly measures at the type section of the Ratawi are probably represented by sandstone in the Zubair Formation in Samawa well No. 1. The boundary with the Zubair Formation is diachronous.

The Ratawi Formation is conformably overlain by the Zubair Formation. The contact is placed at the top of a thin pelley limestone that contains abundant algal debris. In Samawa well No. 1 the Ratawi and Yamama contact is recognized by the first appearance of pelley limestone.

The lower part of the Ratawi Formation, containing limestone intercalations, probably corresponds approximately in stratigraphic position to the Garagu Formation of northern and central Iraq. The upper part of the formation is represented by coarse-grained sandstones, silts, and silty shales in the wells of the Awasil area, which have been identified as Zubair Formation. Hence, the upper part of the Ratawi Formation is equivalent in age to the lower part of the Zubair Formation of Awasil, Fullujah, and Mileh Tharthar wells.

ZUBAIR FORMATION

TYPE SECTION, THICKNESS, AND EXTENT

The type section of the Zubair Formation is in BPC well Zubair No. 24 (lat 30°22'00" N., long 47°36'46" E.; alt 42.53 ft; completed Aug 22, 1953). The formation lies between drilled depths of 10,368 and 11,645 feet (1,277 ft thick). In the vicinity of the type area in the Zubair oil field, this formation has an average thickness of 1,250 feet. It is widespread in the subsurface sections of southwestern Iraq, where it has been penetrated in BPC wells Ghalaian No. 1, Kifl No. 1 and 2, Luhais No. 1, Nahr Umr No. 3, Rachi No. 1, Ratawi No. 1, Rumaila wells, Safayi No. 1, Samawa No. 1, Shawiya No. 1, Tuba No. 1, Ubaid No. 1, and Zubair wells and in the Mosul Petroleum Co. well Awasil No. 5.

In a belt extending from Luhais well No.1 (incomplete thickness) to Samawa well No.1 (1,581 ft) and Kifl well No.1 (1,612 ft), the formation shows slight thickness variation. Westward from this belt, the formation abruptly decreases in thickness to 785 feet in Ghalaian well No.1; therefore, the maximum thickness is to be expected northeast of a line between wells Kifl No.1 and Samawa No.1.

DETAILED LITHOLOGIC DESCRIPTION

The Zubair Formation is heterogeneous and exhibits rapid lateral and vertical variations, though it has

a widespread distribution. In the type locality it consists of the following broad, main lithologic units:

- | | Thickness
(feet) |
|---|---------------------|
| 6. Shale, black, pyritic, fissile, with rare intercalations of gray siltstone; four beds (10-15 ft thick) of very fine grained gray cemented sandstones, calcareous in places and grouped into two beds separated by shaly partings in upper half of unit; 18 ft of sandy limestone toward top is separated from overlying Shu'aiba limestone by a shale band ----- | 286 |
| 5. Sandstone, light-brown, oil-stained, naturally white, fine-grained, with subangular grains; contains subordinate shale alternating with siltstone; comprises possibly 9 sandstone beds; grades abruptly into overlying shales; forms "Third Pay" of Zubair field and "Main Pay" of Rumaila field ----- | 428 |
| 4. Shale, black to greenish-black, subsidiary gray calcareous silt intercalations, especially toward middle ----- | 144 |
| 3. Sandstone, light-brown, oil-stained, very fine grained, current-bedded; in places contains thin shaly and carbonaceous or lignitic foliations; intercalated in places with gray siltstone, greenish-gray mudstone, and hard greenish-black fissile resinous shale containing plant remains; grades to underlying and overlying shale through siltstone; constitutes "Fourth Pay" of Zubair field ----- | 239 |
| 2. Shale, greenish-black, fissile, pyritic, hard; some intercalations of gray locally calcareous siltstone in lower half ----- | 127 |
| 1. Sandstone, white, in places oil-stained, very fine grained, locally silty, separated from underlying Ratawi Limestone by 10 ft of black shale; grades upward into shale through siltstone ----- | 53 |

At Samawa well No.1 the Zubair Formation, apart from a thin shale band at the top, is represented throughout by characteristically weakly cemented or loose crossbedded quartz sands; streaks of lignitic shale are common but insignificant in amount. Silt and silty shale intercalations are chiefly confined to the lower part of the formation. Northward at Kifl well No.1, the Zubair comprises buff, gray, or white fine to medium unfossiliferous sand and sandstone with pyritic calcareous cement that alternates with thin bands of silt stone, shales, and rare lignite.

The Zubair Formation interfingers basinward laterally and vertically into the Ratawi Formation. The occurrence and relationship of the two formations were dependent on their position on the shield and in the basin. The influence and significance of this phenomenon is indicated in the shale units of the Zubair Formation in the type area.

DIAGNOSTIC FOSSILS AND AGE

Fossils diagnostic of the Zubair Formation are *Orbitolina* cf. *O. discoidea* Grs, *Choffatella decipiens*

Schlumberger, *Cristellaria* spp., *Cuneolina* sp., *Trochololina* sp., *Eoogyra* sp., *Cerithium* sp., and *Lima carteroniana* d'Orbigny (at base).

According to recent investigation and stratigraphic reinterpretation by M. Chatton, the age of this formation ranges from Valanginian to Barremian over southwestern Iraq. Owing to the strong diachronism of the formation, its age varies according to the paleogeographic position and sedimentary history. In southern Iraq this formation is of Hauterivian and Barremian ages only. Though the full Valanginian to Barremian sequence has been found in wells Samawa No. 1 and Kifl No. 1, farther north the sequence of Zubair Formation may extend into Aptian as it does at Awasil well No. 5. Elsewhere, these age limits may be expanded, extended, or restricted.

CONTACTS AND EQUIVALENT UNITS ADJACENT TO SOUTHWESTERN IRAQ

The contact of the Zubair Formation with the underlying Ratawi Formation is conformable, gradational, and diachronous and is placed at the highest Ratawi limestone bed underlying the shale and siltstone of the Zubair Formation. In wells Kifl No. 1 and Awasil No. 5 the Zubair Formation overlies the Yamama Formation. The contact with the overlying Shu'aiba Formation is conformable and is placed at the top of black fissile shales. In Safawi well No. 1, where the Shu'aiba Formation is missing, the Nahr Umr Formation overlies the Zubair Formation directly, presumably with unconformity.

In Saudi Arabia the Zubair Formation may pass into the Buwaih and Biyadh sandstones, predominantly into the Biyadh.

ECONOMIC ASPECTS

Commercial quantities of oil have been discovered in the sands and sandstones of the Zubair Formation in several localities in southwestern Iraq, including the Zubair oil field, Rumaila oil field, Luhais well No.1, and Kifl well No.1. Present oil production of the Basrah Petroleum Company comes from the two oil fields. The details and reservoir characteristics follow.

Zubair field

The "Third Pay" oil occurs in sands of the Zubair Formation under a cover of dark shales and units of the formation itself. The reservoir section is thus a sandstone shale complex, some 320 feet thick, in which four main and significant members can be distinguished, averaging about 200 feet in total thickness. The oil is undersaturated by roughly 2,000 psi and, therefore, no primary gas cap is present. Water has been struck on both flanks at approximately the same elevation. The

quality of the oil varies with structural position, so that crestal wells have a gas-oil ratio of approximately 800 cu ft. per bbl (cubic feet per barrel) and low flank wells, of 600 cu ft per bbl. Oil gravities show a similar trend, suggesting some gravitational segregation of oil within the reservoir. The average value is 36° API. Porosity averages 20 percent permeability, 250-400 millidarcies. A spacing of 1 well to 866 acres on a diamond grid, has been adopted and pressure interference on a small scale has been noted.

The wells average 11,000 feet in depth and are completed by selective-shape charge perforation of the 5½-inch oil string which is cemented through the producing section. Initial flowing pressures average 1,600 to 1,800 psi at 5,000 barrels per day. A feature of production has been the large salt content of wells high in the structure. No water has been detected, but the oil may contain as much as 1,000 pounds of salt per 1,000 barrels. It is believed that this salt is derived from water-saturated siltstones associated with oil sands; a desalting plant is being installed. The reservoir mechanism to date has been expansion of the undersaturated oil. This process has resulted in a steep pressure decline. A poorly effective water drive may be operative on one flank.

The "Fourth Pay" oil occurs in sands of the Zubair Formation, but is separated from the "Third Pay" by some 220 feet of black shale and siltstone. It consists of a thinner but similar sandstone-shale complex, containing, however, a better quality oil of average gravity, 42° API. A large primary gas dome is present. Sand characteristics are less favorable than the "Third Pay", and high-pressure drawdowns are associated with relatively low production rates.

Rumaila Field

The reservoir section at Rumaila is in the same geological formation as at Zubair but contains a much higher proportion of sand and the shale and siltstone members are noticeably absent. Porosity averages 25 percent and permeability, 1,000 millidarcies. The oil is even more undersaturated than at Zubair; that is, saturation pressure is 2,500 psi below initial reservoir pressure. A horizontal oil-water level was proved to exist throughout the reservoir.

Some variation of quality with structural position is present but is not nearly so marked as at Zubair. The gas-oil ratio averages 700 cu ft per bbl, and the gravity of the crude, 36° API. The field has only recently gone on production and, so far, by oil expansion. From the characteristics of the reservoir sand, a water drive may be expected.

SHU'AIBA FORMATION

TYPE SECTION, THICKNESS, AND EXTENT

The type section of the Shu'aiba Formation is in BPC well Zubair No. 3 (lat 30°23'01" N., long 47°43'29" E.; alt 51.9 ft; completed Feb. 21, 1951). The formation lies between drilled depths of 9,962 and 10,132 feet (170 ft thick) and forms a transgressive limestone unit which is fairly widespread in the subsurface sections of southern Iraq wells. It has not yet been found in the Cretaceous outcrops in the western desert. In the subsurface sections throughout the Al Basrah area, its thickness ranges between 150 and 350 feet. West of the Euphrates River it thins to about 100 feet between As Samawah and An Najaf. Farther west the thickness decreases to about 80 feet in the vicinity of Ash Shawiyat and Al Ubaid. In Ghalaian ash Shabicha the thickness is not more than 30 feet. The Shu'aiba Formation disappears by pinching out in the Safawi well east of Birkat az Zafiri on the Iraqi-Saudi Arabian border.

DETAILED LITHOLOGIC DESCRIPTION

The Shu'aiba Formation consists mainly of cream-colored orbitolinid, detrital, in places chalky, pseudoolitic limestones and recrystallized skeletal limestones. Some argillaceous, sandy, and shaly intercalations occur toward the base.

DIAGNOSTIC FOSSILS AND AGE

Orbitolina cf. *O. discoidea* Gras, *Choffatella decipiens* Schlumberger (at base only), and globigerinids in upper parts are diagnostic forms in the Shu'aiba Formation, which is Aptian in age.

CONTACTS AND EQUIVALENT UNITS IN AREAS ADJACENT TO SOUTHWESTERN IRAQ

The contact with the underlying Zubair Formation is conformable and gradational and is taken at the top of the first shale bed below *Orbitolina* cf. *O. discoidea* limestone. Normally the contact is easily picked on the electric logs; however, owing to the gradational nature of the contact, it is sometimes difficult to detect on the logs. The top of the shale is taken as a marker and called the Z/1 marker (see section on "Zubair Formation").

The contact with the overlying Nahr Umr Formation may be unconformable, and it indicates a sharp lithological change from the porous elastic limestones of the Shu'aiba Formation to the silts and shales of the basal Nahr Umr Formation. The contact has been designated as the SH/1 marker and can easily be located at a sharp negative deflection of the selfpotential curve of the electric log, which coincides approximately with a substantial increase of rate of penetration. Above

this marker there are local beds of limestone which some authors include in the Shu'aiba Formation; however, for the present purpose they have been considered as reworked limestone deposited in the wake of a regressive sea.

The Shu'aiba Formation passes laterally into the Zubair Formation in Iraq and Kuwait. This explains in part the westward thinning from the Basrah area. It is possibly represented in part by the Biyahd Formation, with which a gradational relationship is postulated.

ECONOMIC ASPECTS

The Shu'aiba Formation is of no direct economic significance, although its equivalent, which has good porosity, contains oil in the Abu Hassa area, Abu Dhabi. In Iraq the formation is marked by a zone in which circulation, is lost; thus drilling is hazardous.

NAHR UMR FORMATION

TYPE SECTION, THICKNESS, AND EXTENT

The type section of the Nahr Umr Formation is in BPC well Nahr Umr No. 2 (lat 30°44'15" N., long 47°41'45" E.; alt 21.7 ft; completed Mar. 4, 1950). The formation lies between drilled depths of 8,688 and 9,321 feet (633 ft thick) and is named after the well. It is extensive in the subsurface, and has been found in all deep subsurface sections in the Basrah area, in the western desert, and in central Iraq and also in the wells of Nahr Umr, Zubair, Tuba, Rumaila, Ratawi, Rachi, Luhais, Ubaid, Samawa, Shawiya, Safawi, Ghalaian, Kif, Awasil, and Nafatah.

In its greatest development, the formation trends northward, parallel to the Euphrates River. The maximum thickness of about 1,100 feet is in the subsurface sections of Zubair field. This thickness is comparable to that recorded in Kuwait (average thickness 1,150 ft). This area of great thickness is seemingly confined to a narrow belt, to the east of which the formation is sharply reduced in thickness, whereas to the west the change is gradual. The thickness of this formation in the Rumaila-Luhais area ranges between 900 and 800 feet. Farther west, in the Ubaid Ghalaian area, the thickness diminishes to between 400 and 600 feet. Northward there is a general reduction in thickness; in the Samawa-Shawiya area the formation ranges between 200 and 500 feet. Farther north in the Awasil and Nafatah areas the formation thins to between 200 and 300 feet.

DETAILED LITHOLOGIC DESCRIPTION

In the type locality the Nahr Umr Formation can be subdivided from core and electric-log evidence into

three distinct lithologic units. These units from top to bottom are:

	Thickness (feet)
3. Shale, hard, homogenous, black, interbedded with black to green-gray shale containing streaks of fossiliferous skeletal black limestones some of which contain molluscan shells and sponge spicules	144
2. Limestone, marly and in places dolomitic, orbitolinitid, in part globigerinal, with streaks and intercalations of greenish-black shale; predominantly black shale rich in small molluscs and in places containing pyritized slightly calcitic ostracodes, with bands of detrital forbitolinitid skeletal limestones. (Dair Limestone Member)	118
1. Sandstone, fine- to medium-grained, brown; loosely or well-cemented with well-rounded quartz grains or, in places, glauconite; a few intercalations of black siltstones, shale containing fossil plants, amber, and lignite; streaks of chalky partly detrital limestone	371

These units maintain their general characteristics throughout a large area including Samawa, Ratawi, Rachi, Kif, Rumaila, and Zubair. Westward and northwestward, however, the shales interdigitate and intergrade laterally into sandstone, and distinguishing the Nahr Umr Formation from the Zubair Formation becomes difficult when one reaches the Safawi area, where the underlying Shu'aiba is missing. Eastward, marl, shale, and limestone replace this sandstone and its terrigenous components. Southward, in Kuwait, the Nahr Umr Formation is lithologically divisible into two members which have been called the Third and the Fourth Sands.

In central Iraq the Nahr Umr is recognized only in the subsurface sections of the Mosul Petroleum Co. wells Awasil No.5, Fallujah No.1, Nafatah No.1, and Mileh Tharthar No.1. In these wells the thickness of the formation ranges between 200 and 300 feet, and the formation comprises coarse- to medium-grained sandstones and subordinate shales. Correlation of the unit, as found in the wells of the Awasil area, with the Nahr Umr Formation of the Basrah area, rests upon lithology and upon homotaxy relative to the preceding Shu'aiba Formation and succeeding Maaddud Formation. In the Awasil and Nafatah areas the unit was originally named the "Nafatah Sand" (H. Huber, unpub. data), but this name has never been sustained by publication and is now obsolete.

The view was prevalent at one time that the Nahr Umr Formation was directly equivalent to the Rutbah Sandstone Formation of the Rutbah-Wadi Hauran region of western Iraq, and the name Rutbah (or Rutbah) Sand was originally applied to the unit in Basrah and also to the sequence of formations (Wara, Maud-

dud, and Nahr Umr) which are now included within the Burgan subgroup of Kuwait (Owen and Nasr, 1958). The name Rutba Sand is a collective name that includes the current Ahmadi, Wara, Maaddud, and Nahr Umr Formations of the Kuwait succession. The term Rutbah (or Rutba) Sandstone is not now applied in the subsurface sections of southern Iraq and Kuwait, as it is now thought that the Rutbah Sandstone Formation of western Iraq is of Cenomanian age and is separated from the Maaddud Formation and underlying Nahr Umr sands by a widespread erosional unconformity. (The Wara Formation of the Basrah area may be directly equivalent to and continuous with the Rutbah Sandstone Formation.)

The Dair Limestone Member thins westward and southward, being replaced by shales and sands. It is not discernible in the Kuwait area.

DIAGNOSTIC FOSSILS AND AGE

Orbitolina cf. *O. discoidea* Gras, *Haplophragmoides* sp., *Cythereis* sp., and *Lezogyra* sp. are diagnostic of the Nahr Umr Formation. The prominent Dair Limestone Member contains *Orbitolina* cf. *O. discoidea* Gras, and *O. cf. O. concava* (Lamarck), algae, and a molluscan fauna including *Plicatula* cf. *P. auressensis* Coquand, *Orbiculoides* sp., *Neithea dutruei* (Coquand), and *Lezogyra* cf. *E. dieneri* (Blanchenhorn). The formation is Albian in age.

CONTACTS

The contact of the Nahr Umr Formation with the underlying Shu'aiba Formation is conformable and gradational; it is placed at the base of the lowest bedded shales of the Nahr Umr Formation and the top of the shale-streaked limestones that make up the highest division of the Shu'aiba Formation. However, in the Awasil area the Nahr Umr Formation rests upon dolomitized Shu'aiba Formation that includes coarse-grained sandstones in direct contact with coarsely granular dolomites that are entirely free from detrital quartz. An emergent episode and depositional break has thus been inferred between the two formations. This contact becomes undistinguishable in the extreme west, where, owing to absence of the Shu'aiba Formation, it is difficult to separate the Nahr Umr Formation from the underlying Zubair Formation. The overlying Maaddud Formation is both conformable and gradational; the contact is placed at the base of the limestone of the Maaddud Formation and at the top of a black shale section.

EQUIVALENT UNITS IN AREAS ADJACENT TO SOUTHWESTERN IRAQ

Between the Awasil area and Makhul well No.1, the Nahr Umr Formation passes laterally into the

limestone-anhydrite-shale-marl sequence of the Jawan Formation, which is between recognizable Maaddud Formation and Shu'aiba Formation. This sedimentary sequence, which is of near-evaporitic facies in its upper parts, contains a marine macrofauna that includes the Albian index fossil *Globiconcha altispira* Whitfield near the base; correlative beds in the Jawan Formation at Jawan have yielded *Knemiceras syriacum* (von Buch), confirming Albian age for the basal Jawan Formation and supporting Albian age for the lower part of the laterally equivalent Nahr Umr. Thin siltstones and silty shales and limestones in the lower part of the Jawan of Makhul well sections may be regarded as far-reaching tongues of Nahr Umr Formation, lying far to the east or northeast of the recognized limits of the unit. The Nahr Umr Formation has been recognized in Kuwait and correlates very well with that in Iraq. In Saudi Arabia its equivalent is included in the Wasia Formation.

ECONOMIC ASPECTS

The upper shaly units of the Nahr Umr Formation form caprocks for any accumulation of oil in the lower sandstones, as they do at the type locality. The Nahr Umr Formation, the Wara Formation, and to some extent the intervening Maaddud Formation, together compose the main reservoir for oil in the Burgan-Magwa-Ahmadi area.

The sand to shale ratio of the unit varies considerably between the various oil fields of the Basrah-Kuwait area. Generally speaking, the sand content increases southward and southward. In the Burgan field, for example, this unit is 1,150 feet thick and is made up almost entirely of sand, whereas in its type locality at Nahr Umr well No.2, the sand to shale ratio is 40:60.

MAUDDUD FORMATION

The Maaddud Formation was defined from the subsurface section of Dukhan well No. 1, in Qatar, by F. R. S. Henson in 1940, but the definition was revised and amended by W. Sugden in 1958, and a reference section in the Basrah area was described by Owen and Nasr (1958).

REFERENCE SECTION, THICKNESS, AND EXTENT

The reference section of the Maaddud Formation is in BPC well Zubair No. 3 (lat. 30°23'01" N., long 47°43'29" E.; alt 51.9 ft; completed Feb. 21, 1951). The formation lies between the drilled depths of 8,517 and 8,923 feet, based on the sharp change in lithology as well as the distinct change in the self-potential curve on electric logs. The limits of the formation were put at 8,457-8,910 feet by Owen and Nasr (1958); however,

those are based solely on electric logs without lithologic evidence.

The formation is 406 feet thick and is fairly extensive throughout southwestern Iraq. It is recorded in the wells at Nahr Umr, Zubair, Tuba, Rumaila, Ratawi, Rachi, Luhais, Ubaid, Samawa, Shawiya, Safawi, Ghalaian, and Kifl. From the Shatt al Arab River the thickness of the formation decreases southwestward from 570 to 430 and 350 feet at the Zubair and Rumaila fields and to 380 and 320 feet at Ratawi and Rachi. At Luhais No. 1 it further decreases in thickness to 291 feet. Northward the decrease is also noticeable at Samawa and Kifl, where 90 to 95-foot thicknesses were recorded. These are less than at Shawiya (111 ft) and in the extreme west at Ghalaian (125 ft). At Safawi and Ubaid there is a great decrease in thickness to about 35 feet. These decreases have generally been attributed to erosion marked by the unconformity between this formation and the overlying Ahmadi Formation.

DETAILED LITHOLOGIC DESCRIPTION

The Maaddud Formation consists mainly of cream-colored microdetrital pseudo-oolitic orbitolinid locally recrystallized limestones and a few thin blue shales; tight, marly, chalky limestones are intercalated especially in the lower half and middle. The limestones are spotted with pyrite. Glauconite has been noted toward the base. These limestones become more porcellaneous northward.

DIAGNOSTIC FOSSILS

Diagnostic fossils of the Maaddud Formation are *Iragia simplex* Henson, *Trocholina altispira* Henson, *T. arabica* Henson, *Orbitolina* cf. *O. concava* (Lamarck), *Rabanitina basraensis* Smout, *Archeolithothamnium* sp., and *Bairdia* sp.

A. S. Sayyab (unpub. data, 1956) studied a suite of Cretaceous ostracodes from the Persian Gulf area, including the Cretaceous section from Zubair well No. 5. He described a rich characteristic fauna, mostly composed of hitherto undescribed species, from the Maaddud Formation.

In the Maaddud Formation in the western desert wells, the fauna includes rare *Cyclammina* sp., *Oligostegina* sp., *Globigerina* sp., *Cuneolina* sp., *Pseudochrysalidina* sp., *Gumbelina* sp., rotalids, gastropods, bryozoans, and algae.

AGE

The Maaddud Formation is Albian in age. Owen and Nasr (1958) considered the age of the Maaddud Formation in the Basrah-Kuwait wells as Cenomanian. Smout (1956) concurred, though admitting the possibility of Albian age, which was favored by Dunning-

ton, Wetzel, and Morton (in Bellen and others, 1959), who made the following statement:

In the Basrah and Kuwait wells, according to Owen and Nasr (1958), the Maaddud is represented by organic, detrital, sometimes pseudo-oolitic, cream-colored limestones with occasional green or bluish shale streaks. It ranges in thickness from only 6 feet, within the Burgan field, to a maximum of over 500 feet in parts of the Zubair field. It overlies Albian Nahr Umr Formation conformably, and is overlain by the Wara Formation, which comprises black silty shales and siltstones (Basrah) and sandstone (Kuwait). The Wara underlies the Cenomanian Ahmadi shale and the contact of the Wara with the Maaddud suggests slight disconformity (Owen and Nasr, 1958).

The fauna of the Maaddud in the subsurface sections previously mentioned includes *Orbitolina* cf. *O. concava* (Lamarck), *O. concava* var. *qatarica* Henson (Awasil and Nafatah), *T. lenticularis* Henson, and *Cyclammina* spp. *Orbitolina* cf. *O. discoidea* Gras is recorded from the lower part of the formation at Makhul, Awasil, and other wells.

It is manifest that the Maaddud has been correctly identified in the Basrah-Kuwait area and in northern Iraq, and it is equally clear that the formation must have been deposited more or less synchronously over the whole region from Qatar to Makhul well 1. The acceptance of Albian age for the formation in Qatar (W. Sugden, unpub. data, 1958) is incompatible with the Cenomanian attribution made by Owen and Nasr (1958) and accepted by Smout (1956).

The evidence assembled from northern Iraq unequivocally favors a late Albian age. The cooccurrence of *Orbitolina* cf. *O. concava* (Lamarck) and *O. cf. O. discoidea* Gras is sufficient to demonstrate pre-Cenomanian age for the lower part of the formation at Makhul, and the constancy of the associated fauna throughout the formation is strong evidence that the age range of the formation is not great. *Orbitolina* cf. *O. concava* is not restricted to the Cenomanian, as suggested by F. R. S. Henson (unpub. data, 1948), but in northern Iraq, at least, it seems to be indicative of Albian age. Specimens attributed to *Orbitolina* cf. *O. concava* occur below a middle and upper Albian ammonite fauna at Naakelekan. Hence the absence of Cenomanian forms, as *Praeaeveolina* spp. and others may be more significant in determining between Albian and Cenomanian age than is the presence of *Orbitolina* cf. *O. concava*.

Orbitolina conclava var. *qatarica* certainly lived on into Cenomanian time, for this form is found with a normal Cenomanian fauna of *Praeaeveolina* spp. in the Rumaila Formation of Basrah and other places (Owen and Nasr, 1958).

Smout (1956) commented that the type locality of *Iragia simplex* Henson is either Cenomanian or so high in the Lower Cretaceous that a Cenomanian occurrence would not be surprising. In fact, the type locality of this species lies about 700 feet below the top of the Qamchuqa limestone in the Rowanduz Gorge. In that section the top of the Qamchuqa is now considered to be of Albian age, and *Iragia simplex* ranges here through late and early Albian, in association with *Orbitolina* cf. *O. coneacea* (Lamarck) and *Orbitolina* cf. *O. discoidea* Gras. Hence the presence of *Iragia simplex* in the Maududd Formation of Basrah wells is supporting evidence for Albian rather than Cenomanian age.

In Awasil and Nafatah the Maududd is separated from the Mahilban by an erosional unconformity, though the Mahilban is of sufficiently late Cenomanian age to allow an early Cenomanian age for the Maududd. It is tempting, however, to correlate the Mahilban-Maududd unconformity, at Awasil, with the slight disconformity reported by Owen and Nasr (1958) between the Wara Formation and the Maududd Formation in Basrah and Kuwait.

The Wara Formation (Owen and Nasr, 1958) may be early Cenomanian or even perhaps late Albian, because, according to R. G. S. Hudson (unpub. data), the overlying Ahmadi Formation contains *Turritella amotisi* Shalem, *T. blanckenhorni* Shalem, *Corbula* sp. juv., *Exogyra conica* (J. Sowerby), *E. lugnesi* (Lartet) and *Aspidiscus* (*Helladastrae*) juv. cf. *A. semhae* Kossmat. Early Cenomanian age is probable for this assemblage (the late Cenomanian age, suggested by fragmentary *Neolobites* sp. from within the Ahmadi, and by *Metoicoceras* sp. (undescribed species) from the basal *Cythereis bahraini* limestone, is ruled out by the occurrence of *Aspidiscus* sp.).

CONTACTS WITH ADJACENT UNITS

The contact between the Maududd and the underlying Nahr Umr Formation is conformable and gradational and is placed at the top of a black shale section.

The Ahmadi Formation overlies the Maududd, perhaps with slight disconformity. In Kuwait, the Wara Formation overlies the Maududd. The Wara has been observed in certain Zubair wells and in Rachi well No. 1. In the Awasil and Nafatah area the Maududd is unconformably overlain by Mahilban. The Maududd Formation does not crop out in Saudi Arabia nor in southwestern and western Iraq.

ECONOMIC ASPECTS

The Maududd Formation is the "Main Pay" limestone or "Second Pay Limestone" of the Bahrain field, and it produces oil in parts of the Burgan field

of Kuwait. In the Basrah area these limestones as a rule are barren of oil.

RUTBAH SANDSTONE FORMATION

TYPE SECTION, THICKNESS, AND EXTENT

The type section of the Rutbah Sandstone Formation is at the northeast end of a promontory lying between the Wadi Ubeila and Rutbah, and about 4 kilometers northwest of the settlement of Rutbah, after which the formation is named. The base of the formation is at approximately lat 33°04'20" N., long 40°12'50" E.

The formation has a thickness of 23 meters, according to Dunnington, Wetzel, and Morton (in Bellen and others, 1959). This formation is widely exposed around Rutbah and as isolated outliers overlying the Mulussa limestone plateau to the east of Rutbah. It occurs also in the Wadi Hauran, east and west of Muhaiwir. The Rutbah Sandstone Formation transgresses an extensive eroded surface which exposes the Bathonian Muhaiwir Formation in the eastern Wadi Hauran and Ga'ara Sandstone of probable Middle Triassic age in the western part of the Ga'ara depression area. The formation pinches out abruptly to the north and northwest between Ga'ara Sandstone and the M'sad Formation. It thickens considerably to the east where it overlies the Bathonian Muhaiwir Formation and is unconformably overlain by Miocene limestone in the vicinity and east of Muhaiwir.

The Rutbah Sandstone Formation at one time was considered to be of Aquitanian (Oligocene) age in the Muhaiwir area, the confusion arising through misdating of the coral fauna of the Muhaiwir Formation as Oligocene. The name "Hauran sandstone" (Hauran Quartzite) was informally applied to the sandstone during this period of misunderstanding, and, though never defined or published, this name has been fairly widely used for sandy sediments, which occur below the lower Miocene limestones in other areas. The unpublished "Hauran sandstone" is a junior synonym for the Rutbah Sandstone Formation; and its use is now abandoned; it should not be confused with the "Zor Hauran Formation", which is now formally defined as the rock unit which intervenes between the (Liassic?) Uba'id Formation and the (Upper Triassic?) Mulussa Formation, in the Wadi Hauran, below the Rutbah Sandstone Formation, west of Muhaiwir.

The name Rutbah (or Rutba) sand (or sandstone) was formerly applied to the Nahr Umr Formation of southern Iraq, and also to those units of the Kuwait succession which are now collectively designated as the Burgan subgroup (Owen and Nasr, 1958). For the most part, such usage was confined to unpublished

reports of oil companies, but Barber (1948) included in his publication a stratigraphic table for the Kuwait succession which groups the Ahmadi, Wara, Maaddud, and Nahr Umr Formations of current classifications as subdivisions of the Rutbah sand.

DETAILED LITHOLOGIC DESCRIPTION

Varicolored, white and ferruginous coarse to fine sands and sandstones, locally cemented to quartzites, make up the formation. Basal parts are possibly of continental origin; the upper parts are marine. No diagnostic fossils have been found.

AGE

The Rutbah Sandstone Formation is pre-Cenomanian or early Cenomanian, as it is overlain by the upper Cenomanian M'sad Formation. It is Upper Triassic to post-Triassic or Upper Triassic, as it is underlain unconformably by Upper Triassic Mulussa Formation. Its age is not ascertained within these units at the type locality.

CONTACTS AND EQUIVALENT UNITS IN ADJACENT AREAS

The Rutbah is underlain by the Mulussa Formation; the contact is unconformable, erosional, and discordant. Overlying the Rutbah is the M'sad Formation, with transitional, gradational contact which is placed at the base of the first definite limestone bed above the continuous sandstone of the Rutbah sandstone.

According to Dunnington, Wetzel, and Morton (in Bellen and others, 1959), the Rutbah Formation is homotaxial with the "gres lignitifere" of Zumoffen (1926) and with the so-called Nubian sandstone of the Lebanon and other places. It has been loosely equated with the Nahr Umr Formation of the subsurface sections, with which it may be continuous, but it is much more probable that these two units are genetically distinct and that the Rutbah Sandstone Formation overlies the eroded outcrops of the Nahr Umr in the area between Muhaiwir and Awasil.

Whereas the Nahr Umr Formation is considered to be of early Albian age, grading upward into the late Albian Maaddud Formation, the Rutbah is probably of Cenomanian age at its type locality, where it is overlain by the upper Cenomanian M'sad Formation. The M'sad Formation is probably approximately correlative in age with the Mahilban Limestone of the Awasil area, and the Rutbah Sandstone Formation at Rutbah is probably the same age as part of the hiatus between the Maaddud and Mahilban Formations at Awasil. This interpretation is preferable to the earlier held concept that the Rutbah and Nahr Umr Formations compose a single diachronous sandstone deposit.

The Rutbah may also be equated with the Wasia Formation of Saudi Arabia.

ECONOMIC ASPECTS

The Rutbah Sandstone Formation forms a good aquifer in western Iraq, where a number of Iraq Petroleum Company water wells along the pipeline draw their water from this formation.

AHMADI FORMATION

REFERENCE SECTION, THICKNESS, AND EXTENT

The reference section of the Ahmadi Formation is in BPC well Zubair No. 3 (lat 30°23'01" N., long 47°43'29" E., alt 51.9 ft, completed Feb. 21, 1951) between drilled depths of 8,070 and 8,517 feet (447 ft thick). The formation is widespread in the subsurface sections of southwestern Iraq in the wells of the Nahr Umr, Rumaila, and Zubair fields and in wells Tuba No.1, Ratawi No.1, Rachi No.1, Luhais No.1, Samawa No.1, Kif No.1 and 2, Shawiya No.1, Ubaid No.1, Safawi No.1, and Ghalaissan No.1. Thus far the greatest thicknesses of the formation are in the Basrah area and are between 400 and 550 feet. This thickness trend extends to Samawa well No.1 (437 ft thick) and almost to Luhais well No.1 (382 ft thick). Over Ash Shawiyat and Ubaid areas the thickness decreases to about 300 feet. In the extreme west at wells Safawi No.1 and Ghalaissan No.1, recorded thicknesses are 185 and 249 feet, respectively. At Kif well No.1 a thickness of only 56 feet is recorded.

DETAILED LITHOLOGIC DESCRIPTION

The Ahmadi Formation at the reference subsurface section can be subdivided into three lithologic units, which are from top to bottom:

	Thickness (feet)
3. Shale, greenish-gray, fissile, ostracode-bearing, interbedded with gray ostracode-bearing marl and streaks of arenaceous detrital limestone containing <i>Cythereis</i> sp. and <i>Cytherella</i> sp.	163
2. Limestone, gray, marly with streaks of green shale (Tuba Limestone Member)	177
1. Shale, light-blue to gray, pyritic, fissile, with streaks of gray soft locally calcareous marls containing <i>Haplophragmoides</i> , <i>Cythereis</i> sp., and <i>Cytherella</i> sp.	107

A similar sequence has been recognized in wells Luhais No.1 and Samawa No.1. However, this formation changes its character westward where it becomes more like the Wara Formation. At Safawi well No.1 it becomes predominantly red, brown, and green fissile somewhat silty shale containing glauconite toward the base. Northward in the Kif area, the sequence is highly dolomitized and predominantly calcareous.

Glauconitization at the base of Ahmadi may be indicative of shallowing, and a possible unconformable contact with the underlying Maaddud Formation was thus postulated. Southward the Ahmadi Formation has been considered to grade laterally into the Wara Formation of Kuwait, and northward into the Rutba Sandstone Formation.

The neritic Tuba Limestone Member in the Basrah area increases in thickness eastward toward the basin by replacing the shaly components, and the facies becomes more and more Oligosteginal till it cannot be distinguished from that of the Rumaila. In the more basinward areas the upper shales of the Ahmadi merge into the neritic Mishrif Formation.

DIAGNOSTIC FOSSILS AND AGE

Turritella spp., *Corbula* sp., *Exogyra conica* (J. Sowerby), *Exogyra luynesii* (Lartet), *Neolobites* sp., *Parasmilia* sp., *Metacoeceras* sp., *Aspidiscus* (*Helladastraea*) juv. cf. *Aspidiscus semhae* Kossmat, and species of *Haplophragmoides*, *Flabellina*, *Vaginulina*, *Ammobaculites*, *Gumbelina*, *Lenticulina*, *Frankelina*, *Haplophragmium* have been recognized at most places, but elsewhere *Prævalvulina cretacea* (d'Archiac), *Pseudocyclammina* cf. *P. hedbergi* Maync and *Meandro psina* sp. have been recognized and indicate Mishrif influence.

In 1956, Sayyab described a suite of ostracodes from the Ahmadi Formation of the Zubair well No. 5. This suite includes *C. ovata* Roemer and a large and characteristic assemblage of undescribed new species, including some new genera.

The formation is Cenomanian; Sayyab (1956) favors Albian age for this formation on the basis of the ostracode fauna, and W. Sngden (unpub. data, 1958) argues for late Albian age for the presumably correlative lower parts of the Khatiyah Formation of Qatar.

In most of the wells in southern Iraq, the Ahmadi Formation lies unconformably over the Maaddud Limestone, although it is underlain by Wara Formation in places; however, recognition of the Wara in these wells is difficult. The base of the Ahmadi Formation is placed at the base of a shale (at times a gray dense limestone), the M/1 marker. The Ahmadi is overlain by the Rumaila Formation, with which a conformable and intergradational contact has been postulated. Equivalent units in adjacent areas are the Khatiyah, Wasia, Rutbah Sandstone, and Wara Formations, in part.

ECONOMIC ASPECTS

The Ahmadi Formation constitutes the caprock that retains oil within the underlying sands of the Burgan

Subgroup in the Kuwait oil fields. In the Basrah oil fields area of southern Iraq, although the formation is present, there is not thus far any indication that it functions as a caprock. The Ahmadi here is the cause of a great deal of caving in drilling wells, if a well-controlled drilling-fluid system is not maintained.

RUMAILA FORMATION

TYPE SECTION, THICKNESS, AND EXTENT

The type section of the Rumaila Formation is in BPC well Zubair No. 3 (lat 30°23'01" N., long 47°43'29" E.; alt 51.9 ft.; completed Feb. 21, 1951), where it lies between drilled depths of 7,605 and 8,070 feet (465 ft thick). This formation has widespread distribution in southwestern and central Iraq, and owing to facies changes at the expense of its thickness the formation varies considerably from one place to another in the oil fields of southern Iraq. Generally, it ranges in thickness between 140 and 500 feet. Except for local variations, the general thinning is gradual and westward. At wells Samawa No.1 and Shawiya No.1 the thickness decreases to slightly more than 200 feet. In the south between wells Ubaid No.1 and Safawi No.1, the thickness ranges between 170 and 180 feet. Westward the thickness increases slightly, as compared with the thickness at wells Samawa No.1 and Shawiya No.1, to 239 feet at Ghalaian well No.1. At Kifl well No.1 the equivalents of this formation attain the exceptional thickness of about 900 feet.

DETAILED LITHOLOGIC DESCRIPTION

Lithologically the Rumaila Formation can be subdivided into two units as follows:

	Thickness (feet)
2. Marl, buff to brown, chalky, foraminiferal, oligosteginal; intercalations of crystalline leached-out limestones; chalky to dense limestones; shale streaks ...	265
1. Limestone, cream-colored, dense, cryptocrystalline; oligosteginal; some is marly with some streaks of shale	200

The lithology of this formation undergoes considerable lateral and vertical variation, depending on the interdigitation of chalky marls and limestones. One such manifestation is observed in wells Kifl No.1 and Awasil No.5, where the formation has been subdivided into three formations—Mahilban, Fahud, and Maotsi. The Rumaila interdigitates with the overlying Mishrif Formation and the underlying Ahmadi Formation, and in the Rutba area it is postulated to merge into the exposed M'sad Formation.

DIAGNOSTIC FOSSILS AND AGE

Diagnostic fossils in the Rumaila Formation are *Oligostegina Globigerina* spp., *Orbitolina concava* var.

gatarica Henson, *Gumbelina* sp., *Nummuloculina* sp., *Begia* sp., miliolids, valvulinids, and rotalids. The formation is Turonian and Cenomanian in age.

CONTACTS AND EQUIVALENT UNITS IN ADJACENT AREAS

The Ahmadi Formation underlies the Rumaila Formation conformably. The contact is placed at the top of the black fissile ostracode-bearing shales. The Rumaila may rest directly on the Maaddud limestones in central Iraq. It is overlain by the Mishrif Formation; the contact is conformable, diachronous, and intergradational at the top of *Oligostegina*-bearing limestone. In the area of wells Samawa No. 1, Ghalaian No. 1, and Kifl No. 1, the Rumaila Formation is directly overlain by the lagoonal evaporitic Kifl Formation.

The Rumaila Formation is composed of subbasinal facies and may pass into the more basinal Dokhan facies. In facies and age the Rumaila Formation is equivalent to the Mahilban, Fahud, and Maotsi Formations of central Iraq. M. Chatton (unpub. data) recommended adoption of the name Rumaila Formation to replace the three formation names. This formation is not differentiated from the Mishrif Formation in wells of southeastern Kuwait, where these two formations are replaced by the Magwa Formation. The Magwa Formation has been eroded from the crestal areas of the Burgan, Magwa, and Ahmadi structures, but occurs in progressively increasing thicknesses down the flanks.

KIFL FORMATION

The Kifl Formation has been defined by M. Chatton (unpub. data) to include the evaporite facies of the Cenomanian-lower Turonian sedimentary cycle in southern Iraq.

TYPE SECTION, THICKNESS, AND EXTENT

The type section of the Kifl Formation is in BPC well Kifl No. 1, (lat 44°11'14.55" N. long 32°15'08.04" E.; alt 141 ft; completed July 8, 1960). The formation lies between drilled depths of 4,738 and 4,830 feet (92 ft thick).

The unit has been found in the BPC wells Ubaid No. 1, Shawiya No. 1, Samawa No. 1, Ghalaian No. 1, Kifl No. 2, and the Mosul Petroleum Co. wells at Nafatah and Awasil. The distribution of this formation is not limited to the region already mentioned but extends to other parts of the country. In southern Iraq, however, the formation passes laterally by interdigitation into the Mishrif Formation, within a zone extending from east of Ubaid to Shawiya and Samawa. Northeastward the two facies are interbedded. At Kifl itself, Kifl evaporites indicate downward gradation into the Rumaila chalks.

DETAILED LITHOLOGIC DESCRIPTION, FOSSILS, AND AGE

The Kifl Formation is predominantly white crystalline anhydrite with streaks of green marl and chalky pelletal limestone locally having an anhydritic matrix; cream-colored porcelaneous anhydritic marly limestone occurs at the base. The Kifl contains uncommon miliolids and textulariids. Its age is probably late Cenomanian and early Turonian.

CONTACTS WITH ADJACENT UNITS

The Kifl is underlain by the Rumaila Formation (formerly called Maotsi Formation); the contact is conformable, gradational, and is placed at the change from continuous white, creamy *Oligostegina*-bearing chalky limestone below to anhydritic marly limestone. The Khasib Formation overlies it. The contact is unconformable, with a sedimentary break, and is placed at the change from anhydrite below to shale above. No equivalent units in adjacent areas are recorded.

ECONOMIC ASPECTS

The Kifl Formation has no known economic significance; it may induce trapping of oil in the porous section of the Mishrif Formation.

M'SAD FORMATION

TYPE SECTION, THICKNESS, AND EXTENT

The type section of the M'sad Formation is in Wadi M'sad al Rutbah, which runs due north for 20 miles from Jebel Tarayat (lat 32°46' N., long 40°17' E.) to join the Wadi Hauran at Rutbah (lat 33°02' N., long 40°07' E.). The formation is about 211 feet thick. It is widely exposed in the area north of Rutbah; sections have been measured at An Nadhara, Khasm Mulussa, Wadi Semhat, Ras Semhat, Rutbah, Wadi Mulussa, and "Hill 270."

The occurrence of sands and sandy limestones within the unit is a feature of this heterogeneous formation in the area of the type locality. One thin sand bed, remarkably constant over the area of exposure, separates the main, limestone-dominated upper part of the formation from the thin, basal limestone unit.

DETAILED LITHOLOGIC DESCRIPTION

The M'sad Formation consists of alternating shallow marine limestones, shell breccias, microdetrital limestones, chalky buff and white limestones, pink marls, and sandy marls and sands; a thin sandstone tongue occurs near the base.

In the vicinity of the type locality the M'sad Formation grades conformably into and perhaps interdigitates laterally with the underlying Rutbah Sandstone Formation. It underlies an erosional unconformity H. H. Boesch, (unpub. data) over which the Maestrichtian

tian Tayarat Formation transgresses. The Turonian, lower Senonian, and Campanian Stages are not represented by sediments in the Rutbah-Jebel Tayarat area, though formations of these ages enter the succession in the area to the east, southeast, and south.

DIAGNOSTIC FOSSILS AND AGE

No fossils are recorded from the type locality of the M'sad Formation. The limestones of this unit elsewhere carry a rich if ill-preserved macrofauna from which *Nerinea cochleaeformis* Conrad was identified by A. Keller and H. H. Boesch (unpub. data). Rudists, including *Caprinula* sp. and *Eoradiolites liratus* Conrad, were also recorded by A. Keller (unpub. data) but have not been confirmed in postwar collections. Recent collections, identified by R. G. S. Hudson and J. Robinson, include *Nerinea cretacea* Conrad and *N. cf. N. gemmifera* Conrad, indicating Cenomanian age, probably late Cenomanian.

The associated microfauna, which is represented throughout the formation, both above and below the thin sandstone previously mentioned, includes *Meandropina* cf. *M. vidali* Schlumberger, *Cuneolina* cf. *C. cylindrica* Henson, *Dicyclina* cf. *D. gatarica* Henson, rare *Præaeveolina* sp., *Begia* spp., *Pseudochrysalidina conica* (Henson), and *Toberina* cf. *T. bingistani* (Henson). The microfauna is probably of late Cenomanian rather than early Cenomanian age and is unlikely to be younger than Cenomanian.

The age of the formation has not been ascertained at the type locality. Elsewhere in the vicinity of the section the formation is middle Cretaceous, early Cenomanian at the base and probably early Cenomanian throughout.

CONTACTS AND EQUIVALENT UNITS IN ADJACENT AREAS

The underlying unit of the M'sad Formation is the Rutbah Sandstone Formation; the contact is gradational and conformable and is placed at the base of the lowest limestone bed above the continuous Rutbah.

The M'sad Formation is overlain by the Tayarat Formation; the contact is unconformable owing to an erosional break in sequence which omits sediments of Turonian to intra-Maestrichtian ages. The contact is placed at the base of the localized basal conglomerate of the Tayarat Formation.

On the basis of age, microfauna, and microfacies, the M'sad Formation is considered to be correlative with the Mahilban limestone of the Awasil area and the Mishrif Formation (part) of southern Iraq, from both of which it may be distinguished by its heterogeneity. Distinction will be difficult in areas where the sand and marl components are subordinate, and in

intermediate areas the name M'sad and Mahilban Formation may be necessary.

MISHRIF FORMATION

TYPE SECTION, THICKNESS, AND EXTENT

The type section of the Mishrif Formation is in BPC well Zubair No. 3 (lat 30°23'01" N., long 47°43'29" E.; alt 51.9 ft; completed Feb. 21, 1951). The formation is between drilled depths of 7,204 and 7,605 feet (401 ft thick).

In the Basrah fields this formation ranges between 350 and 550 feet in thickness. Its eastern extension is unknown. Thickness trends follow a northerly direction, as if the Mishrif were deposited over a shoal extending basinward from the Arabian shield across the Kuwait-Basrah region, bordered on the east by the main Balambo basin and on the west by a subsidiary, shallower "Rumaila" basin. Thus, geographically, rocks of Mishrif type may be restricted to a narrow belt. To the west the Mishrif is only a few feet thick at wells Samawa No. 1 and Safawi No. 1 and is absent at Ghalaisan well No. 1.

According to Dunnington, Wetzel, and Morton (in Bellen and others, 1959), in the Rutbah area of the western desert the Mishrif is probably represented in outcrop by the correlative M'sad Formation which carries a microfauna similar to that of the Mishrif Formation. The rudist *Eoradiolites liratus* Conrad, reported here by A. Keller, is believed to occur also in the subsurface Mishrif Formation (W. Sugden and E. Hart, unpub. data, 1957). The Mishrif Formation is not represented in southeastern Kuwait, where equivalent sedimentary rocks form the upper part of the Magwa Formation.

DETAILED LITHOLOGIC DESCRIPTION

The Mishrif facies, which is thickly developed throughout the Basrah area, consists of neritic sedimentary rocks, mostly limestones and, in places, shales. The limestones are variable in texture and may be oolitic or pelletal, shelly, and coquinooid types which contain algae, rudists, bryozoans, corals, and miliolids; in places there are indications of offshore deposition.

The following is a detailed lithologic sequence in the type section, based on reinterpretation of the electric logs:

	Thickness (feet)
8. Limestone, fine-grained, limonitic, fresh-water, containing <i>Charophytes</i> and marl; interbedded with black shale having some light-buff streaks -----	50
7. Limestone, white-buff, fine-grained, fractured or stylolitic, marly, partly pseudo-oolitic and microbreccious with streaks of greenish-black shale and pale-buff marl toward base -----	26

6. Marl, whitish-buff, algal, and greenish-black shale ----	12
5. Limestone, brown and white, dense, detrital, containing gastropods, rotalids, and sponge spicules; partly pseudo-oolitic and contains rare chalky streaks and thin green shale intercalations -----	68
4. Limestone, cream to white or brownish-buff, porous, partly very shelly and foraminiferal; contains bands of rudists, <i>Cisalveolina</i> sp., <i>Begia</i> sp., <i>Dicylelina</i> sp., <i>Diclyococcus</i> sp., miliolids, and others -----	136
3. Marl, white to buff, chalky, oil-stained in places -----	16
2. Limestone, porous, oil-stained, brown to light-buff; leached-out fossils; contains calcite veins and floods of miliolids, <i>Begia</i> sp., <i>Cisalveolina</i> sp., <i>Dicylelina</i> sp., <i>Taberina</i> sp., <i>Praealveolina</i> sp. and others -----	58
1. Limestone, buff to brown, algal, contains miliolids or <i>Cisalveolina</i> sp.; very dense at base -----	35
Total -----	401

At Samawa well No.1 the formation is very thin and barely recognizable, consisting of 32 feet of tight, fine dolomite containing some miliolids.

According to Dunnington, Wetzel, and Morton (in Bellen and others, 1959) the *Chara* limestone which occurs at the top of the Mishrif in near-crestal wells in the Zubair field is missing in most other areas. The limonitization of the upper beds of the Mishrif and the abrupt facies change from algal limestone to globigerinal marly limestones strongly suggests nondeposition and an emergent episode, with erosional termination of the Mishrif. On the other hand, close correlation between wells and fields in the Basrah area does not confirm any significant erosional convergence below the base of the Khasib Formation. In Kuwait, however, the Mishrif and Rumaila Formations and the upper parts of the older Ahmadi Formation were eliminated at the erosional unconformity which preceded the Upper Cretaceous transgression, and the hiatus narrows, significantly, to the limonitized surface atop the Mishrif as the Basrah area is approached (Owen and Nasr, 1958, fig. 5).

DIAGNOSTIC FOSSILS AND AGE

Fossils found in the Mishrif Formation include *Chara* sp., *Pemolaculus ireane* Elliott, *Cisalveolina* sp., *C. fallax* Reichel, *C. lehneri* Reichel, *Praealveolina cretacea* (d'Archiac), *P. cretacea* var. *tenuis* Reichel, *Multipirina iranensis* Reichel, *Dicylelina gatarica* Henson, *Taberina bingistani* (Henson), *Pseudochrysalidina conica* (Henson), *Begia* spp., *Cozites subaivensis* Smout, and *Trocholina* spp.

Recent stratigraphic work in Iraq by M. Chatton and E. Hart (unpub. data) dates the Mishrif Formation as Cenomanian and early Turonian. Owen and Nasr (1958) attributed this formation to the Turonian; however, according to Dunnington, Wetzel, and Morton (in Bellen and others, 1959):

A. H. Smout (1956) has described numerous species of the foraminiferal genus, *Begia*, from the Mishrif formation of the Basrah area. He argues for Turonian age for the rich faunas of the lower part of the unit, but the *Alveolinidae* are of Cenomanian rather than Turonian age in Iran, and the rudist evidence from Rumaila wells and macrofossil evidence as to age of the correlative M'ad Formation are strongly in favour of a Cenomanian attribution also. The upper part of the formation could be Turonian, but the *Pemolaculus* flora near to the top of the unit matches that from the Mahliban Formation of the Awadi area (G. F. Elliott, unpub. data) which is separated by unconformity from the presumably Turonian Fakhad Limestone.

CONTACTS AND EQUIVALENT UNITS IN ADJACENT AREAS

The contact of the Mishrif Formation with the underlying Rumaila Formation is conformable and is placed at the change from oligosteginal-globigerinal limestone below to neritic limestones, with miliolids, *Begia* spp., and larger Foraminifera above; thus, the contact is one of normal lateral and vertical gradation. The contact with the overlying Khasib Formation is disconformable, owing to a considerable sedimentary hiatus (Bellen and others, 1959). The Mishrif Formation commonly is conformably overlain by a thin evaporitic lagoonal Kifl Formation, as in some of the western desert subsurface sections. In the extreme west, for example at Safawi well No.1, where the Khasib is absent, the Tanuma shales rest directly but unconformably on a few feet of the Mishrif Formation.

The Mishrif Formation may be equated with at least the upper part of the Wasia Formation of Saudi Arabia, though the Wasia is a different facies.

ECONOMIC ASPECTS

According to staff members of the Iraq Petroleum Company (oral commun., 1956), medium oil (26° API) can be produced from the limestones of the Mishrif Formation in the Zubair and Rumaila oil fields of the Basrah Petroleum Company, where it constitutes what is called the "Second Pay."

KHASIB FORMATION

TYPE SECTION, THICKNESS, AND EXTENT

The type section of the Khasib Formation is in BPC well Zubair no. 3 (lat 30°23'01" N., long 47°43'29" E.; alt 51.9 ft; completed Feb. 21, 1951). The formation lies between drilled depths of 7,040 and 7,204 feet (164 ft thick). It has been found in all subsurface sections in southern and western Iraq except in well Safawi No.1. To date (1964) these sections include wells in the Nahr Umr, Zubair, and Rumaila fields; in the wells Rachi No.1, Ratawi No.1, Luhais No.1, Samawa No.1, Kifl No.1 and 2, Ubaid No.1, Ghalaisan No.1, and Shawiya No.1; and in the wells in northeastern Kuwait. The formation was not identified, however, in

southeastern Kuwait, where it probably has equivalents in the lower part of the Gudair Formation that are complete. The Gudair thins toward the structural uplift of Burgan, and equivalents of the Khasib and Tanuma Formations are probably eliminated by progressive overlap (Owen and Nasr, 1958). The thickness distribution and variation is complicated by facies interrelation with the overlying Tanuma Formation. The Khasib thickens basinward to the northeast to as much as 300 feet, whereas a belt, 200 feet thick, may follow the Euphrates River very closely between wells Kifl No.1 and Nahr Umr No.3. In the Basra fields the thickness ranges between 17 and 195 feet. At wells Ratawi No.1 and Rachi No.1 thicknesses of 140 and 118 feet respectively, were recorded. Westward, at wells Ubaid No.1 and Ghalaisan No.1, the thickness decreases to 95 and 77 feet, respectively, and in Safawi well No.1 the formation's identity is completely lost.

DETAILED LITHOLOGIC DESCRIPTION

Lithologically, the type section of the Khasib Formation can be subdivided into two units as follows:

	Thickness (feet)
2. Limestone and chalk, light gray, very marly, slightly dolomitic, with subordinate streaks of black shale	95
1. Shale, dark-gray or greenish-gray, fissile, alternating with globigerina-gumbeloid and dolomitic fissile buff marly limestones	60

DIAGNOSTIC FOSSILS AND AGE

Fossils found in the Khasib Formation are *Globigerina* sp., *Gumbelina* spp., and *Oligostegina*. Sayyab (1956) identified three new ostracode species from the Khasib Formation of Zubair well No. 5. Other microfossils, which include *Globotruncana lapparenti* subsp. and *G. leupoldi* Bolli from Zubair well No. 1 and *G. stuarti* (de Lapparent) from Nahr Umr well No. 1, were recognized in this formation by Dunnington, Wetzel, and Morton (in Bellen and others, 1959). The Khasib Formation is Senonian (early?), according to Owen and Nasr (1958).

Since Owen and Nasr did not recognize any break within the Mishrif Formation, or within the overlying sequence of the Khasib, Tanuma, and Sa'di Formations, the interpretation that the Khasib-Mishrif contact involves no hiatus in sedimentation implies an older age than late Campanian for the base of the Khasib. The Mishrif Formation is considered to be not younger than Turonian (Owen and Nasr indicated Turonian age, but Cenomanian age for at least the lower part of the Mishrif was argued by others. See section on "Mishrif Formation.") Recently, however, M. Chatton and E. Hart (unpub. data) established the

age of this unit as middle Turonian and early Coniacian.

CONTACTS AND EQUIVALENT UNITS IN ADJACENT AREAS

The contact of the Khasib Formation with the underlying Mishrif Formation is disconformable, being between oligosteginal shales above and limonitic limestones with Charophytae below. In Ubaid No. 1 and Kifl No. 1 and 2, the Khasib Formation rests directly on the Kifl evaporites. Owen and Nasr (1958) indicated that the contact between the Khasib and the underlying Mishrif is disconformable in the Basrah area and unconformable on structural highs in Kuwait.

In the Basrah area this unconformity is represented by a thinning of sediments and by a fresh-water limonitic *Chara*-bearing limestone at the top. This limestone is overlain conformably by the transgressive Khasib Formation of the Aruma Group. The contact with the overlying Tanuma Formation is conformable at the change from black fissile shales above to gray marly limestones below.

In northeastern Iraq the Khasib passes into the basinal lower limestones of middle Turonian and lower Coniacian Kometan Formation and Gulneri shales. It is represented in southeastern Kuwait in the lower part of the Gudair Formation.

ECONOMIC ASPECTS

The Khasib Formation has no economic value. It causes some trouble in drilling wells by caving and sloughing.

TANUMA FORMATION

TYPE SECTION, THICKNESS, AND EXTENT

The type locality of the Tanuma Formation is in BPC well Zubair No. 3 (lat 30°23'01" N., long 47°43'29" E.; alt 51.9 ft; completed Feb. 21, 1951). The formation lies between drilled depths of 6,900 and 7,040 feet (140 ft thick). It occurs in all the following deep subsurface sections in southwestern Iraq: wells in the Zubair, Rumaila, and Nahr Umr fields and Ratawi No.1, Luhais No.1, Ubaid No.1, Samawa No.1, Shawiya No.1, Safawi No.1, Ghalaisan No.1, and Kifl Nos. 1 and 2. According to Dunnington, Wetzel, and Morton (in Bellen and others, 1959), this formation has not been formally recognized in southeastern Kuwait, where equivalents are probably represented by the lower part of the Gudair Formation, though cut out by onlap convergence in areas of structural uplift; however, it is recognized in northeastern Kuwait (Fox, 1957) in a stratigraphic position similar to that of the type area. In southwestern Iraq the greatest thickness of Tanuma occurs along a trend extending from wells Rachi No.1 (190 ft) to Ratawi No.1 (170 ft),

Samawa No.1 (163 ft), and Kifl No.1 (130 ft). Westward from the Basrah area there is gradual thinning of the formation from wells Ubaid No.1 (54 ft) to Shawiya No.1 (49 ft), except at Safawi No.1 (83 ft) where an observable thickness anomaly is due to a complete change of facies of the underlying Khasib Formation. Northwestward there is appreciable thinning toward Ghalaisan well No.1 (15 ft).

DETAILED LITHOLOGIC DESCRIPTION

The Tanuma Formation consists of black shale with streaks of detrital limestone. The shales are fissile and the limestones are gray, marly, microcrystalline, pyritespotted, and detrital; glauconite and dolomite crystals occur throughout. An oolitic limestone streak appears in the upper part of the formation; the ooliths have a core of pyrite or glauconite.

DIAGNOSTIC FOSSILS AND AGE

In the type locality of the Tanuma Formation the detrital limestones contain *Monolepidorthis* sp., *Cristellaria* sp., ostracodes, and bryozoans. A. S. Sayyab in 1956 described some ostracodes, mostly new species, from the Tanuma Formation of Zubair well No. 5. The age of this formation was considered as late Senonian by Owen and Nasr (1958), but the fauna, according to Dunnington, Wetzel, and Morton (in Bellen and others, 1959), seems to justify a late Campanian age. Recently, however, M. Chatton and E. Hart (unpub. data) have considered the age of this formation as late Coniacian. Here it should be remembered that because of the diachronous sedimentation of the formation one may expect extension of the total age limits.

CONTACTS AND EQUIVALENT UNITS IN ADJACENT AREAS

The Tanuma Formation is underlain by the Khasib Formation; the contact is conformable and is placed at the change from black fissile shales above to gray marly limestones below. The contact with the overlying Sa'di Formation is conformable and gradational at the change from globigerinal marly limestone above to black fissile shales below. The Tanuma Formation is recognized in the northern Kuwait subsurface sections. To the southeast it passes into the Gudair Formation. The Tanuma may be correlated with one of the Aruma shales in Saudi Arabia.

ECONOMIC ASPECTS

The Tanuma Formation may be good caprock for the trapping of oil in the Mishrif limestones and to a lesser extent in porous parts of the Khasib Formation. Owing to the tendency of the shales to cave, there may be considerable difficulty in drilling operations.

SA'DI FORMATION

TYPE SECTION, THICKNESS, AND AGE

The type section of the Sa'di Formation is in BPC well Zubair No. 3 (lat 30°23'01" N., long 47°43'29" E.; alt 51.9 ft; completed Feb. 21, 1951). The formation lies between drilled depths of 6,013 and 6,900 feet (887 ft thick). No outcrop in southwestern Iraq has so far been designated as Sa'di Formation, although the unit reaches a thickness of 1,279 feet and widespread subsurface distribution, which seems to be in the Rumaila area. Westward, this thickness decreases to from 500 to 600 feet between wells Samawa No. 1 and Ubaid No.1. Further decreases in thickness to 400 ft, were observed near the Iraqi-Saudi Arabian border. A similar decrease occurs northward, where at Kifl well No. 1. Further decreases in thickness to 400 ft were thickening is recognized at Awasil well No.5 (475 ft) and at Nafatah well No.1 (575 ft). The Sa'di Formation, because of nondeposition and erosional cutoff, is not represented in the general Ga'ara-Rutbah area. The true thickness variation cannot be evaluated realistically without paleogeographic and paleogeologic reconstruction of the conditions which prevailed during and after the formation of the Sa'di sediments.

DETAILED LITHOLOGIC DESCRIPTION

The Sa'di Formation can be subdivided into two units in the type locality as follows:

	Thickness (feet)
2. Limestone, white to buff, chalky, marly, slightly dolomitic, fossiliferous with fossil contents decreasing upward; rare green calcareous shale streaks -----	562
1. Marl, greenish-gray to gray, with rare dolomite crystals and pyrite; globigerinal; ostracode bearing; contains some calcareous dark-gray to greenish-gray shale intercalations; upper 190 ft of this unit is recognized as Hamrin marl -----	825

These general characteristics persist westward to the vicinity of Ubaid well No.1, and they are also obvious in Kifl well No.1. "Basinwards, as in Nahr Umr No.2 well," according to Dunnington (1958), "the sequence becomes practically all marl with only a few marly limestone beds." Southward toward Kuwait the Sa'di in Bahra well No.1 is between 5,025 and 5,600 feet thick, but thins considerably toward Burgan and eventually disappears.

DIAGNOSTIC FOSSILS AND AGE

The Sa'di Formation is very fossiliferous and contains abundant microfauna and flora, especially in the lower part. The fossil generally listed are *Bairdia* sp., *Cytherella* sp., *Brachythere* sp., *Nodosaria* sp., *Globigerina* spp., *G. cretacea* d'Orbigny, *Oligostegina*, *Textularia* sp., *Palmula* sp., *Marginulina* sp., *Cristellaria*

sp., *Globotruncana angusticarinata* Gandolfi, *G. fornica* Plummer, *G. lapparenti lapparenti* Brotzen, *G. lapparenti coronata* Bolli, *G. sigali* Reichel, *G. marginata* (Reuss), and *Præglobotruncana concavata* (Brotzen). Elsewhere, the list may be augmented by the algae *Archaeolithamnium digitatum*, Pfendor *Dissoeladella undulata* (Raineri) Pia, and *Trinocladus tripolitanus* Raineri.

The Sa'di formation is Santonian and early Campanian in age. Owen and Nasr (1958) considered this unit to be late Senonian age. Recently, however, M. Chatton and E. Hart (unpub. data), because of the discovery of *Præglobotruncana concavata* (Brotzen) associated with the other fossils, advocated an age of late Coniacian to early Santonian for the Sa'di; the upper part of the Sa'di being younger, they maintained that its age extends to early Campanian. This may well be the case, at least at some localities, owing to the diachronic sedimentary history of the formation.

CONTACTS AND EQUIVALENT UNITS IN ADJACENT AREAS

The contact of the Sa'di Formation with the underlying Tanuma Formation is conformable at the top of black calcareous shale and at the base of white chalky limestone. The contact with the overlying Hartha Formation is an erosional unconformity corresponding to that noted between the Bahra and Gudair Formations in Kuwait (Owen and Nasr, 1958). Westward and southward the subbasinal Sa'di Formation passes into the neritic Aruma and Gudair Formations in Saudi Arabia and Kuwait.

ECONOMIC ASPECTS

The Sa'di Formation has no known economic value. Owing to the swelling nature of the rock constituents, it may cause stuck-pipe problems during drilling operations.

HARTHA FORMATION

TYPE SECTION, THICKNESS, AND EXTENT

The Hartha Formation type section is in BPC well Zubair No. 3 (lat 30°23'01" N. long 47°43'29" E.; alt 51.9 ft; completed Feb. 21, 1951). The formation lies between drilled depths of 5,590 and 6,013 feet (423 ft thick).

The distribution of this formation in the subsurface sections of southwestern Iraq is extensive: Its thickness ranges between 370 and 765 feet in the Basrah area; gradually increases westward to 1,048 feet in the Ash Shawiya area; and, together with tongues of the Safawi Formation, reaches a maximum of 1,210 feet farther west. From the Kifl area northward toward the Ga'ara massif, the Hartha Formation thins out. Owing to the absence of the intervening Qurna Formation, it

is difficult in some places to differentiate the Hartha Formation from the overlying Tayarat Formation, except possibly by detailed micropaleontologic studies. On the east side of the Ga'ara massif the Hartha Formation is only 210 feet thick at Nafatah well No.1. According to Owen and Nasr (1958), this formation thins out toward northern Kuwait but shows little facies change. They maintained that this lithologic unit has not been precisely delimited in low structural wells in Kuwait, and is missing in structurally high areas of southern Kuwait, owing to erosion or nondeposition. "In the Burgan-Ahmadi area erratic variation in thickness from 50 to 300 feet suggests that the earliest deposits of this formation were laid down in hollows eroded at the top of the underlying Gudair Formation, and the lithology suggests a transgressive phase in this area."

DETAILED LITHOLOGIC DESCRIPTION

The Hartha Formation consists of the following lithologic units:

	Thickness (feet)
4. Limestone, thin-bedded, gray, pyrite-spotted, algal, glauconitic, alternating with dark-gray fissile shale.	35
3. Limestone, buff to gray, recrystallized, globigerinal, algal, with some chalky matrix; passes upward into very marly limestone	86
2. Dolomite, light-brown, crystalline, with shale streaks toward the base	214
1. Marl, light-buff, ostracode-bearing, alternating with green calcareous shale which in places passes into argillaceous pyritic mottled glauconitic limestones.	88

This lithologic sequence varies from place to place and changes laterally according to the paleogeographic position of the formation; for example, in the western desert there is a general tendency toward increase of dolomite content and interfingering of the Safawi anhydrite.

DIAGNOSTIC FOSSILS AND AGE

Fossils recognized in the Hartha Formation are *Globotruncana* cf. *G. stuarti* (de Lapparent), *Cosinella* sp., *Valvulammia* sp., *Ammobaculites* sp., *Monolepidorthis* sp., *Pseudedomia complanata* Eames and Smout, *Brachyocythere* spp., and Bryozoa. In sections other than the type section, the Hartha has yielded *Omphalocyclus macropora* (Lamarck) and *Orbitoides media* in association with *Monolepidorthis* spp. from close to the base of the formation. On the basis of this association, the lower part of the Hartha and the unconformity at its base may be dated fairly closely as being of earliest Maestrichtian or latest Campanian age, probably the latter.

Elsewhere the following fossils were recognized: *Archaeocyclus midorientalis* Eames and Smout, *Sid-*

erolites heracleae (Arni), *Rotalia skourensis* Pfender, *Ogivalia parisiensis* d'Orbigny, *Dicelytina schlumbergeri* Munier-Chalmas, and *Cuneolina cylindrica* Hensler. The formation is Maestrichtian and late Campanian in age.

CONTACTS AND EQUIVALENT UNITS IN ADJACENT AREAS

The contact of the Hartha Formation with the underlying Sa'di Formation is an erosional unconformity in the Basrah area and also in Kuwait, where it overlies the Gudair Formation. The contact with the overlying Shiranish Formation (formerly Qurna) was stated to be disconformable by Owen and Nasr (1958), and was placed at the top of white chalky glauconitic limestone and at the bottom of soft gray marl. This relationship has recently been contested by M. Chatton (unpub. data), who believes that the contact is conformable. In the extreme west at Safawi well No. 1 this formation is overlain conformably by the newly defined Safawi Formation. Northwestward, where the intervening formation is missing, the Hartha is overlain directly by the Tayarat Formation.

In southeastern Kuwait the term Bahra Formation has been used to include the combined lateral equivalents of the Hartha and the overlying Shiranish Formations, which are apparently less distinguishable in that area than in the northern Iraq fields, or in northern Kuwait, owing to the lateral southward passage of the Shiranish marls into limestones. The Hartha Formation may have its equivalent within the Aruma Formation of Saudi Arabia.

SAFAWI FORMATION

The Safawi Formation is newly defined to include the evaporitic facies of the upper Campanian and Maestrichtian cycles of sedimentation. As exploratory drilling operations progressed westward from the Basrah area, an appreciable amount of evaporite stringers, increasing in thickness westward, was observed in the Hartha Formation. In the BPC well Safawi No.1 these evaporites are so thick that they merit definition as a formation.

TYPE SECTION, THICKNESS, AND EXTENT

The type section of the Safawi Formation is in BPC well Safawi No. 1, (lat 30°2'45" N. long 43°45'50" E.; alt 1,362 ft; completed Oct. 9, 1960). The formation lies between drilled depths of 2,058 and 2,290 feet (232 ft thick).

This unit, thus far, occurs in the subsurface sections interfingering with the Hartha Formation in the wells Ghalaisan No.1, Kifl Nos. 1 and 2, Shawiya No.1, Ubaid No.1, and Awasil No.5. The occurrence of evaporites in a similar stratigraphic position was ob-

served in the well Makhul No.1, and defined as Dibs Anhydrite Member of the Pilsener Limestone Formation by Dunnington, Wetzel, and Morton (in Bellen and others, 1959).

LITHOLOGIC DESCRIPTION AND AGE

The Safawi Formation is predominantly white, compact hard crystalline anhydrite, with subordinate brown hard crystalline dolomite and buff to gray soft marls. No fossils have been found in it thus far. A Maestrichtian and late Campanian age is assigned to the formation on the basis of its stratigraphic relations with the underlying Hartha and overlying Tayarat Formations.

CONTACTS AND EQUIVALENT UNITS IN ADJACENT AREAS

The lower contact of the Safawi Formation with the Hartha Formation is conformable, and the unit grades into Hartha Formation laterally eastward. The contact with the overlying Tayarat Formation is not well defined owing to the lack of cores; slight unconformity is postulated because of the transgressive nature of the Tayarat.

The Safawi Formation is equated with the Dibs Anhydrite Member of the Pilsener Formation in Makhul well No. 1; the formation has not been recorded in Saudi Arabia.

SHIRANISH FORMATION

In the Basrah area the Shiranish Formation was formerly known as the Qurna Formation; the synonymy is now recognized.

REFERENCE SECTION, THICKNESS, AND EXTENT

The reference section for the Shiranish Formation is in BPC well Zubair No. 3, (lat 30°23'01" N., long 47°43'29" E.; alt 51.9 ft; completed Feb. 21, 1951). The formation lies between drilled depths of 5,202 and 5,590 feet (388 ft thick). It occurs in all deep subsurface sections in the Basrah area and in Kuwait. According to Owen and Nasr (1958), the Shiranish Formation ranges in thickness between 250 and 450 feet, being thinnest in the Rumaila field. There is a general thickening of the formation northwestward, and in the Samawa area it attains a thickness of 550 feet. Westward from that area it thins to about 450 feet in the area of Ghalaisan well No. 1. It passes laterally westward into the neritic Tayarat Formation.

DETAILED LITHOLOGIC DESCRIPTION

The Shiranish Formation consists of buff or ash-gray globigerinal marl, in some places dolomitic, and some marly and detrital limestone beds; it is glauconitic toward the base and contains a rich microfauna.

According to Owen and Nasr (1958), the Shiranish marls in the Basrah area pass in southern Kuwait into white to gray dense marly microcrystalline limestone, which in many places contain gray chert nodules. This calcareous facies has not always been distinguished from the adjacent formations. Similar changes have been observed west of Ubaid well No.1; at Safawi well No.1 it appears that all the Shiranish marls have passed into chalky and marly limestone within the Tayarat Formation.

DIAGNOSTIC FOSSILS AND AGE

Fossils found in the Shiranish Formation are *Cytherella* spp., *Bairdia* spp., *Nodosaria* sp., *Globotruncana* spp., *Cristellaria* spp., *Gyroidina naranjoensis* White, *Anomalina* sp., *Marssonella oxycona* (Reuss), *Gaudryina* sp., *Bolivina ino rassa* Reuss, *Bulinella laevis* (Beissel), *Cibicides beaumontianus* (d'Orbigny), *Bolivina draco* (Marsson), *Textularia cretosa* Plummer, *Gumbelina* sp., and others. The formation is Maestrichtian in age.

CONTACTS AND EQUIVALENT UNITS IN ADJACENT AREAS

The Hartha Formation underlies the Shiranish with slightly disconformable contact. The overlying Tayarat Formation is conformable and gradational; the contact is placed at the junction of dolomitic limestones above and globigerinifer marls below. In the Kif area the Shiranish is directly overlain by the Aaliij Formation with unconformable contact. In southeastern Kuwait the Shiranish Formation passes into the Bahra Formation and in Saudi Arabia into the Aruma formation.

TAYARAT FORMATION

TYPE SECTION, THICKNESS, AND EXTENT

The type section of the Tayarat Formation is the scarp face and crest of Jebel Tayarat (Tayarat, not Ayarat), 21 miles nearly due south of Rutbah, lat 32°46' N., long 40°17' E. A reference section in the BPC well Zubair No. 3 lies between drilled depths of 4,482 and 5,202 feet. The formation is about 98 feet (incomplete) thick at the type locality.

According to Macfadyen (1938), this formation has a widespread outcrop distribution in the Wadian area, south of Rutbah. H. A. Field and K. D. Jones (unpub. data, 1958) described good, but incomplete, sections at Abu Ghar (E. 1183, N. 1156), Jelta solution hole (E. 1202, N. 1173), Wadi Ithayna (E. 1195, N. 1183), Al Jandali (E. 1156, N. 1065), and Wadi Tubal west of Abu Nufuq (E. 1193, N. 1184). (Grid coordinates are shown on pl. 1.) In this general area Field and Jones assigned a minimum thickness of 250 feet for the incomplete Tayarat. South of the Widian and Kif areas,

this formation was found in all deep subsurface sections and in some of the shallow structural holes in the southern desert west of the Euphrates River.

Owen and Nasr (1958) maintained that in the Basrah-Kuwait area this formation is essentially in the same facies as in the type locality, but it is thicker than in outcrop section. Its greatest thickness, 970 feet, seems to be localized in the Rachi well No.1 area, decreasing westward to about 600 feet in the area of wells Ubaid No.1 and Shawiya No.1. It also decreases in thickness northward from Rachi well No.1; in the wells Samawa No.1 and Ghalaian No.1, thicknesses of 344 and 296 feet respectively, were recorded.

Dunnington, Wetzel, and Morton (in Bellen and others, 1959) stated:

Passing northwards from Jebel Tayarat through Jebel Thoba, and towards the western rim of the Ga'ara depression, the Tayarat Limestone is cut out progressively, by the erosion of its upper parts, and also perhaps by onlap convergence. In the section of Hill 270 (Lat 33°18'00" N., long 40°10'30" E.), and Khasn Mulusa (lat 33°18'30" N., long 40°07' E.), the formation is absent, the Palaeocene Umm er Radhuma formation resting discordantly on eroded M'asid formation. The convergence increases northwards, so that, at Ras Semhat, the Umm er Radhuma rests directly on Triassic Ga'ara sandstone.

The details of the erosional convergence from Tayarat to An Nadhara have not been studied.

Owing to the formation's abrupt local lithologic changes and closeness to the Ga'ara massif, further study is needed to elucidate the detailed geological history.

DETAILED LITHOLOGIC DESCRIPTION

The Tayarat Formation consists of rubbly porous limestone that is white, buff, and pink; it is rather chalky, fossiliferous, recrystallized, dolomitized, locally sandy, and is conspicuously more massive at the base.

W. T. Foran (unpub. data, 1940) described the composite Upper Cretaceous section in the Widian area as follows:

	Thickness (feet)
Umm er Radhuma white chalky limestones with silicified limestone nodules (flint?).	
Unconformity, especially in Wadi Tibal region.	
6. Limestone, purplish-gray, fossiliferous, contains <i>Lof-lusia</i> ; yellow marls locally passing to sandstone; gray to white granular gastropodal limestones; and soft yellow limestone	27.2
5. Marl, yellow, varying locally to shale, especially toward southeast; numerous corals in upper part.	19.7
4. Sandstone, yellow, has marly matrix to west, passing into current-bedded ferruginous oolite with rhombohedral calcite in Wadi Ghadfat at Tawil; unit thins out and passes to normal marly shale in region of Wadi Tibal, where it is overlain disconformably by Umm er Radhuma limestones; is comparable with yellow sandstone bed (2 m thick)	

near middle of Tayarat section east of type locality	9.5
3. Marl, yellow, varying to shale	10.7
2. Limestone, gray, hard, dolomitic, rudistid, with several gray marly intercalations (1.4 m) having gritty marly zones, especially toward top and base; contains <i>Omphalocyclus macropora</i> (Lamarck), <i>Eoradiolites</i> , and corals	32.8-98.4
1. Marl, yellow, with some thin limestone intercalations	48.5
7. Unconformity	
M'sad soft yellow limestones containing <i>Nerinea</i> sp.	

W. T. Foran (unpub. data, 1940) called unit 2 the Tibal dolomitic limestone; units 3, 4, and 5, the Tawil Marl; and unit 6, the Tayarat limestone. However, F. R. S. Henson (unpub. data, 1940) and H. A. Field and K. D. Jones (unpub. data, 1958) included all these units in the Tayarat Formation.

Macfadyen (1938) pointed out the presence of a fish bed, in presumably Cretaceous sandy limestones at Gur Ayarat, where abundant teeth but fewer bone fragments and vertebrae were found.

DIAGNOSTIC FOSSILS AND AGE

Fossils in the Tayarat Formation include *Loftusia morgani* Douville and *Omphalocyclus macropora* (Lamarck). According to H. A. Field and K. D. Jones (unpub. data, 1958), the Tayarat limestones contain corals, rudists (including *Eoradiolites*?), gastropods, lamellibranchs, and algae. They maintained that generic identification is often difficult as most of the original structures have been destroyed by recrystallization and some by dolomitization. In addition to the fossils recognized in the type section, the following microfossils have been determined from the subsurface sections: *Lepidorbitoides socialis* (Leymerie), *Orbitoides media* (d'Archiac), *O. apiculata*, *Ogivalia parisiensis* d'Orbigny, *Rotalia skourensis* Pfender, *R. trochidiformis* Lamarck, *Globotruncana* spp., *Dictyoconus* sp., *Dicylella schlumbergeri* Munier-Chalmas, and *Pseudochrysalidina* sp.

For complete faunal assemblages of the Tayarat Formation, reference to the equivalent Aqra Limestone of northern Iraq is recommended. (See Bellen and others, 1959.) The formation is Maestrichtian in age.

CONTACTS

The lower contact of the Tayarat Formation with the M'sad Formation is an erosional unconformity placed at the base of a localized conglomerate. In southwestern Iraq, with the exception of the extreme western region in the vicinity of Sawafi well No.1, where it is underlain by Safawi anhydrites, this formation overlies the Shiranish Formation (formerly Qur-na) conformably with lateral interdigitation.

The upper contact is not present in the type locality, owing to the complete erosion of the overlying formation; however, in the Al Widyan area of western Iraq, though the structural grain of the country is flat, there is strong evidence of an overlap relationship between the Paleocene rocks and the underlying Upper Cretaceous Tayarat Formation.

Macfadyen (1938) described this area as follows: "Nearly the whole of the Wadian (Al Widyan) is covered with flat-lying limestones occasionally conglomeratic. These are believed to be wholly of Eocene and Cretaceous age. Since the lithology is generally similar, and recognizable fossils mostly leached out, the Eocene-Cretaceous boundary appears to be unmappable without a great expenditure of time and labour."

According to W. T. Foran (unpub. data, 1940), the contact of the Cretaceous with the overlying Paleocene formations is readily recognizable throughout the exposed area; he placed the contact at the level of the lowest appearance of *Loftusia* and the lowermost chalk containing bluish opaline quartz geodes. One or both of these are commonly near the contact. Later investigators such as H. A. Field and K. D. Jones (unpub. data, 1958) agreed with this view and have placed the contact a short distance above the last appearance of *Loftusia*, at the first recognizable break below the chalk containing nodular cherts and flints. In the deep subsurface sections of southwestern Iraq, the Tayarat Formation is generally overlain by the Umm er Radhuma Formation.

EQUIVALENT UNITS IN ADJACENT AREAS

According to Dunnington, Wetzel, and Morton (in Bellen and others, 1959), "Formations closely comparable with Tayarat are known at outcrop in Saudi Arabia (Aruma formations; R.A. Bramkamp and M. Steineke 1952; W.H. Thralls and R.C. Hasson, 1957, and so forth) and in well sections in Arabia, and in Qatar (Sismisima formation, W. Sugden 1958, MS)."

ECONOMIC ASPECTS

The Tayarat limestones are porous and occupy an extensive area in Al Widyan. Macfadyen (1938) stated that this area is an almost flat-lying Eocene and Cretaceous limestone terrane that has very gentle slope and drainage to the east. The annual rainfall averages less than 10 millimeters, and in summer and autumn this area constitutes the most waterless part of Iraq. A very considerable proportion of the rainfall probably percolates deeply underground through solution channels in the limestone, and the ground water is thus beyond reach of shallow wells; however, deep drilled wells near the underground solution channels

would probably yield water. A detailed account of this subject was given by Macfadyen (1938, 127-135). Minor quantities of phosphatic material may be found in the fossiliferous and chert beds in the area south and west of Rutbah.

CENOZOIC TERTIARY

The Tertiary System includes the Paleocene, Eocene, Oligocene, Miocene and Pliocene series. Rocks of Oligocene age are not recognized in southwestern Iraq because of a major break due to nondeposition, pre-Miocene erosion, or both. Tertiary rocks there are composed of more than 6,500 feet of sediments.

PALEOCENE AND EOCENE

Rocks of Paleocene and Eocene age are represented by four formations that are described in succeeding discussion. The upper Eocene is not represented, perhaps because of pre-Miocene erosion.

UMM ER RADHUMA FORMATION

Reference sections and thickness

The Umm er Radhuma Formation was originally named in Saudi Arabia. Owen and Nasr (1958) referred to a supplementary type section from the Basrah area in BPC well Zubair No. 3 (lat 30°23'01" N., long 47°43'29" E., alt 51.9 ft., completed Feb. 21, 1951). The unit occurs here at drilled depths of between 2,980 and 4,482 feet. The formation crops out in the western desert of Iraq, where for the convenience of field mapping the exposed part has been subdivided into the Basita Beds and the Ghurra Beds.

The type location of the Basita Beds is at the section of a scarp about 50 kilometers west-southwest of Waqisa wells and 2 kilometers southwest of triangulation point S 85. The type location of the Ghurra Beds is about 8 kilometers southwest of Aydahah, near the track at Saddat al Batn. The formation is 1,502 feet thick (458 m); it has been found in all deep surface sections west of the Euphrates and Shatt al Arab Rivers, more specifically in the wells of Nahr Umr, Zubair, and Rumaila oil fields, Tuba No. 1, Ratawi No. 1, Rachi No. 1, Luhais No. 1, Ubaid No. 1, Samawa No. 1, Shawiya No. 1, Ghalaisan No. 1, and Safawi No. 1. The thickness of this formation is extremely variable; the greatest thickness (1,633 ft) was recorded in the Ubaid well No. 1. The thickness appears to decrease both westward and northward, for at wells Shawiya No. 1 and Ghalaisan No. 1 the thickness is 1,202 and 975 feet, respectively. At the extreme western wall, Safawi No. 1, where the formation is exposed, the thickness in the subsurface section is only 858 feet.

Extent

According to Bellen (Bellen and others, 1959), the Umm er Radhuma Formation is exposed over the western part of Iraq, west of a line joining Nisab (Ansab), Ash Shabakeh, and Al Lasaf. For field-mapping purposes, H. Huber (unpub. data, 1941) recognized two units there, mainly on the basis of their topographic expression as scarps in the otherwise rather flat desert.

The Umm er Radhuma outcrops form a strip 20 kilometers wide that extends northwestward from Qalib ar Rufayat-Nisab (Ansab), with a few inliers over Ar Ruwagarea, through Habbas and Jal al Batn. About 25 kilometers southeast of Al Jumaymah, another strip of the Umm er Radhuma Formation crops out under the Zahra Formation and follows the general northwesterly trend. Between Jumaymah and Jal al Batn, the Umm er Radhuma Basita Beds commonly crop out as inliers in the erosion depressions within the Zahra Formation. Farther north, owing to the absence of the Zahra Formation, the two strips of the outcrops form one major belt more than 45 kilometers in width in the region of Hagai al Hawara, especially between Al Lu'ah in the east, and Birkat al Al Aqabah in the west. The region is strewn with outliers of Zahra Formation. Between As Shubrum and Aydahah, several outliers of the Dammam Formation Wagsa Beds occur directly on the Umm er Radhuma Basita Beds. Southwest of the Jal al Batn scarp the Basita Beds are folded and fluted and contain minor contortions from the foot of the scarp itself along a belt 2-5 kilometers wide. In this area the Basita limestone has an extensive outcrop. Farther north, the width of the outcrop on the Iraqi side constricts to 30 kilometers between Al Jill and Athamin, mainly because the greater part of the formation extends into Saudi Arabia. At Athamin as well as Al Athman, outliers of Wagsa Beds of the Dammam Formation can be recognized on the Umm er Radhuma. From Al Jill toward Wagsuh (Wagsa) there is a sharp westward swing, or curve, in the distribution of the outcrop, resulting in the Basita plateau. In this area the Umm er Radhuma is generally confined between the Hagai al Basita-Ash Shaba-Hagai Al Wagsa feature and Al Ghurra. This nearly continuous outcrop ends near Chebritiya, north of where the formation occurs as isolated inliers, seen either within the Zahra Formation on the Dammam Formation. These inliers, which are of variable dimensions, occur in the area of Wadi al Khirr, Al Ghurabiya, Sahb Nauwman, Guwairat al Halib, and Ruwaiyat as Sahal. From this extensive outcrop, northward from Al Makmin (Machmi), only a narrow belt of the Umm er Rad-

huma crops out along the Az Zawr feature to Wadi Al Ubayyid, where it follows this wadi eastward. In this region the Umm er Radhuma disappears under the Damnam Formation on one side and under the Zahra Formation on the other; however, it reappears west of a line from Faidha al Adyan, Aglat al Khail, and Abu Infuq. Here it covers a large territory south of the Wadi Tiba where dissection causes the Upper Cretaceous Tayarat Formation to form the wadi floors, especially in the Wadi al Jaudali, Shaib al Ubaydat, Wadi al Ubayyid and Wadi al Mira. The general outcrop distribution elsewhere is clearly indicated on the geological map (pl. 1).

In the type locality of the Ghurra Member, the section is only 118 feet (36 m) thick; however, in Safawi well No.1 the unexposed part has a greater thickness. A true thickness measurement for the Basita Beds is difficult to make, owing to the width of the exposure and its relation to the overlying formation. Denudation has removed the highest beds from most of the Basita plain, but the most complete section is probably that of Al Batn at the type locality, where its thickness is only 49 feet (15 m). Here, as the overlying Damnam Formation Wagsa Beds are unconformable, the top of the section may show the highest existing Basita Beds. According to Bellen (Bellen and others, 1959), the thickness of a composite section near Aydahah, in the Batn scarp near the frontier with Saudi Arabia, is 705 feet (215 m).

W. T. Foran (unpub. data, 1940) reported a thickness of 348 feet (105 meters) for the Umm er Radhuma Formation. In the Wadi Ghadaf the thickness was estimated by H. A. Field and K. D. Jones to be more than 50 meters. They found representative sections at Al Hisichiyat (E. 1166, N. 1160) and Al If Hada (E. 1140, N. 1110).

Bellen (Bellen and others, 1959) stated:

This formation also occurs at surface in western central Iraq. Along the western rim of the Ga'ara depression it transgresses over the pre-Tertiary outcrops of the Maestrichtian Tayarat Formation and the Cenomanian M'sad Formation and Rutbah Sandstone Formation onto deeply eroded Middle Triassic Ga'ara Sandstone. It is absent from the southwestern parts of the Ga'ara and from the Wadi Haura.

Detailed lithologic description

The Umm er Radhuma Formation consists of anhydritic and dolomitic limestone, which is mostly dull white or buff, microcrystalline, and porous. Chert occurs in the higher part of the formation (Bellen and others, 1959).

In the outcrops at the type location, the Ghurra Beds comprise limestone that is white to gray, partly very hard and recrystallized, saccharoidal, partly leached,

and well bedded and that contains oblate siliceous concretions and chert nodules and layers at some levels.

The Basita Beds at the type locality consist of gray marly hard thick to massive-bedded limestones alternating with white and yellow saccharoidal well-bedded limestones and gray dense recrystallized dolomitic thin-bedded limestones containing chert nodules. Hard roughly concentric limestone concretions as much as 75 centimeters in diameter occur sporadically on the Basita Beds between Aydahah and Nisab. Their origin is not fully understood.

In the Al Widiyan country the Umm er Radhuma Formation consists mostly of alternating soft friable chalks, sporadic dolomitic chalks, bedded chalky limestones, and thin porcelaneous silicified limestones containing subordinate marl, shale, and chert horizons. Chert, flint, quartz vugs, and geodes are distributed generally throughout the sequence, but are better developed to the south. Some shell banks occur in the limestones, for example, 2 kilometers north of Wishashia (E. 1202, N. 1167). The upper chalky zone contains *Operculina libyca* Schwager. Southward, the formation becomes a fissile yellow shale overlying the *Operculina* horizon and the chalky zone includes several irregular zones of ferruginous and siliceous limestone. In the Al Widiyan area a zone composed of large oblate spheroids of siliceous limestone occurs about 20 meters from the base. Owing to the differential hardness, these also strew the plain after erosion of their soft chalky crust. Eastward, the Umm er Radhuma passes into basinal Aaliqi facies, as in the Kif wells.

Diagnostic fossils and age

Fossils in the Umm er Radhuma Formation are rare, but one horizon at the top contains *Alveolina dolioformis* Schwager, *A. oblonga* d'Orbigny, and *A. ovoidea* d'Orbigny. *Operculina libyca* Schwager has also been reported. R. G. S. Hudson (unpub. data, 1951) recorded *Pseudomithat* (*Lucina*) *gigantea* Deshayes and *Turritella* cf. *T. carinifera* Deshayes.

The fossils of the Ghurra Beds are both nondiagnostic and scant; they consist chiefly of *Valvulina* sp., miliolids, rare *Alveolina* sp., molluscs, ostracodes, and algae. In contrast the Basita Beds contain a great variety of fossils. The following were originally determined by F. R. S. Henson and R. G. S. Hudson: *Alveolina* spp., *A. primaeva* Reichel, *Bigennerina* sp., *Dictyoconoides*?, *Dictyoconus* gr. *walnutensis* Carsey, miliolids, *Nummulites* spp., *Operculina libyca* Schwager, *peneroplids*, *Saudia* spp., *S. cf. discoidea* Henson, *Spirulina* sp., *Textularia*, *Valvulina* sp., ostracodes, *Lucina* sp., *Cardita* sp., *C. aegyptiaca* Frass, *Lima* sp., *Dentalium*?, *Corbula* sp., *Arca* sp., *Tellina* sp.,

Venus sp., *Anomia* sp., *Turritella* sp., *Voluta* sp., *Conoclypeus* aff. *C. delanoui* de Loriol, *Echinolampas* sp., and various other molluscs and echinoids, as well as fish fragments and algae. The formation is Paleocene and early? Eocene in age.

Contacts and equivalent units

The Upper Cretaceous Tayarat Formation underlies the Umm er Radhuma with major unconformity. In the outcropping areas "in western central Iraq, along the western rim of Ga'ara depression it transgresses over the pre-Tertiary outcrops of the Maestrichtian Tayarat Formation, and the Cenomanian M'sad Formation and Ruba Sandstone Formation, onto deeply eroded Middle Triassic Ga'ara Sandstone" (Bellen and others, 1959). For further comments about the contacts, see the section on "Tayarat Formation."

The Rus Formation overlies the Umm er Radhuma conformably in the supplementary type section. In the outcrops of western Iraq, where the Rus Formation is absent, the Dammam Formation Wagsa Beds overlie the Umm er Radhuma Formation unconformably.

The Umm er Radhuma Formation is recognized in Kuwait and Saudi Arabia, the type section of the formation being within Saudi Arabia.

Economic aspects

Ground water.—The areas where the Umm er Radhuma limestones crop out are very dry and arid. From data of Macfadyen (1938) it is inferred that the water supply in these areas is in direct relation to the rainfall and that in deep wells the supply is due to percolation downward by means of solution holes—such as those of Chebretiya, Kusra (E. 1225, N. 1160), Jelta (E. 1202, N. 1173), Wishashia (E. 1202, N. 1167), Mus-sir al Awajj (E. 1205, N. 1228), and Wadi Ghadaf (E. 1188, N. 1195)—with storage in such cavities or in some porous horizon at depth. He also maintained that because of apparent scarcity of faulting and folding in the desert, the geologic structure is generally of little help in locating water. The varying quality of the waters, where not due to concentration by evaporation, is due to the heterogeneity of the rocks and to the rainfall being in contact with somewhat variable soluble constituents on its way down from the surface. The lithologic character of the strata is extremely variable, and gives rise to some marked quantitative and qualitative differences in the analyses of the waters. For full details, reference to Macfadyen's (1938) work is recommended.

Sulfur and gypsum.—Macfadyen (1938) referred to the occurrence of native sulfur and gypsum at Chebretiya, some 60 kilometers west of Ash Shabakali (Sha-

bicha), where he described the occurrence and formation of solution structures.

A dry well leads into a double swallow hole, and two vast, roughly circular chambers being 35 metres and 60 metres deep, respectively, and each 50 metres in diameter. They are situated close together, so that the chambers intersect, though at the surface they are a short distance apart, the second, deeper, chamber being partially roofed over. At the base of the first a great mass, some 30×20×25 metres in size, of an admixture of white secondary gypsum and native sulphur, which latter has been worked by the Bedouin for ages, the marks of their tools being seen everywhere. The mass must presumably contain something of the order of 1,000 metric tons of free sulphur. Traces of malachite are also found associated. The whole phenomenon seems to have been caused by an acid spring, or the oxidation of underlying pyrites, which has resulted in the presence of free sulphuric acid. The gypsum tastes strongly acid, and is reported to rot the clothes of those who work there, a report fully confirmed by the rotting effect on the cotton bags and paper in which the samples collected were stored. The swallow holes were clearly dissolved out of the limestone seen in the walls, the portion converted into gypsum having now vanished in solution. A channel five metres square, unexplored, leads out underground from the base of the second chamber, in which there is neither gypsum nor sulphur deposited. A rough section was measured in the walls as follows:

0-3 m. Weathered white shale.

3-60 m. A series of rather soft limestones, marly limestones, and white chalk. Conspicuous bands of flint at 9 m. and 12 m. At 12-13.8 m. a band of small calcite nodules, simulating casts of larger foraminifera, grooves of quartz crystals, and chalcodony are common, particularly in the lower part. No fossils were recognized.

The strata are nearly flat bedded, but a very slight westerly dip was seen in the section of the walls of the chambers.

Phosphates.—Some traces of phosphates may be found in the Umm er Radhuma Formation in the fossiliferous horizons and in horizons containing chert and flint.

RUS FORMATION

Reference section, thickness, and extent

The type locality of the Rus Formation is in Saudi Arabia at lat 26°19'.5 N., long 50°10'.0 E. A supplementary section in Iraq was given by Owen and Nasr (1958) in BPC well Zubair No.3 (lat 30°23'01" N., long 47°45'29" E.; alt 51.9 ft; completed Feb. 21, 1951) and between drilled depths of 2,673 and 2,980 feet (307 ft, or 94 m, thick); however, the formation is thicker elsewhere in the Basrah area, especially between the Zubair field and Luhais well No.1, where evaporites ranging in thickness between 300 and 700 feet have been drilled. Northward, this thick Rus facies extends to wells Samawa No.1 and Shawiya No.1, where it is represented by 200 to 350 feet of evaporites.

This formation does not crop out in the western desert, and it seems to change its facies and pass into limestone east of wells Ubaid No.1 and Ghalaian No.1,

where no Rus Formation has been recognized. The stratigraphic position of the Rus Formation equivalent in outcrop is difficult to define. Bellen (Bellen and others, 1959) has equated the Huweimi (chalk), Shabicha and Sharaf units, and the Wagsa unit of the Dammam Formation with this formation. This would imply that the Rus evaporites pass westward into the Dammam limestones. None of these units has been correlated as yet with any of the limestone beds within the Rus Formation in the subsurface sections. Bellen (Bellen and others, 1959) maintained that none of them is recognizable in wells east of the outcrop area.

Detailed lithologic description

The Rus Formation is predominantly massively bedded white and blue tinted crystalline anhydrite with alternations of thin unfossiliferous limestone, blue shale, and marl. Westward, this evaporitic sequence passes laterally into the Dammam Formation.

Age

The Rus Formation is probably early Eocene (Bellen and others, 1959) in age; no diagnostic fossils have been found. The exact age of the formation is difficult to demonstrate. In the subsurface sections the Rus Formation is sandwiched between the overlying Dammam Formation and the underlying Umm er Radhuma Formation.

According to Bellen (Bellen and others, 1959), the base of the Dammam Formation is of middle Eocene age in subsurface sections but contains a lower Eocene fauna in outcrop. He maintained that it is perfectly possible that the two lower units of the Dammam Formation in the field (the Wagsa Beds and the Sharaf, Shabicha and Huweimi Chalk Beds) change facies toward the offshore regions into part of the Rus Formation as found in the wells. Thus the age of the Rus Formation can indeed be early Eocene. Similar age attribution has been given to this formation in Saudi Arabia (Steineke and others, 1958).

Contacts and equivalent units

The lower contact of the Rus Formation with the Umm er Radhuma Formation is possibly conformable, and the upper contact with the Dammam Formation is unconformable, according to Bellen (Bellen and others, 1959). However, this may be locally conformable, and a gradational contact is advocated on the basis of the lateral facies passage of the two formations.

DAMMAM FORMATION

Type and reference sections

The type locality of the Dammam Formation is in Saudi Arabia at lat. 26°17'03" N, long 50°07'07" E. The supplementary type section chosen by Owen

and Nasr (1958) from Al Basrah (Basra) area is in the BPC well Zubair No. 3 (lat 30°23'01" N, long 47°43'29" E.; alt 51.9 ft; completed Feb. 21, 1951). The formation lies between drilled depths of 1,935 and 2,673 feet (738 ft thick).

Outcrops of this formation in western Iraq were divided into 10 field units for mapping convenience by H. Huber and R. M. Ramsden (unpub. data, 1944-45). According to Bellen (Bellen and others, 1959), these units have no status as formations or even as members, but it is essential and convenient for future investigation to mention their type localities, which are in descending stratigraphic order as follows:

Tuqaylid Beds, about 5.6 miles (9 km) west of Tuqaylid water well on the Tuqaylid scarp.

Ghanimi Beds, east of triangulation point C 26, near Khasman ad Duda on the At Traq scarp.

Barbak Beds, in prominent hills at Barbak and Diud in the southeastern part of the Galaib area.

Rudhuma Beds, in the cliff to the northwest of Chadd, west of Abu Rudhuma.

Chadd Beds, at the north end of the Chadd "structure."

Shawiya Beds, in a small wadi, north-northwest of triangulation point 5.2, to the north of the Ash Shawiyat depression.

Huweimi Beds, 4.3 miles (7 km) west of Ash Shabakah (Shabicha) police post, along the Nukhayb track.

Shabicha Beds, at triangulation point S 25 about 4.3 miles (7 km) west of Ash Shabakah (Shabicha) police post, along the Nukhayb track.

Sharaf Beds, northeast of the Jil water wells along the track leading to Sulman.

Wagsa Beds, in the vicinity of Waqisah (Wagsa) water wells. The greatest thickness of the Wagsa Beds is on the white cliffs east and north of Wagsa wells, from which the name is taken. At the prominent point S 86, 5 km south of the wells, there is a section nearly 30 meters thick.

Thickness and extent

The Dammam Formation is 738 feet (225 m) thick in Zubair well No. 3. This formation is extensive in subsurface and surface distribution west of the Euphrates and Shatt al Arab Rivers. Its thickness in the Al Basrah oil fields and in the Basrah Petroleum Company exploration wells Luhais No. 1 and Rachi No. 1 ranges between 600 and 800 feet. A slightly greater thickness (835 ft) was found in Ratawi well No. 1. The Company's other exploration wells, such as Samawa No.1, Shawiya No.1, Ghalaisan No.1, and Ubaid No.1, which were drilled directly into the exposed Dammam Formation, penetrated incomplete sections of less than 400 feet, excluding the 350- and 245-foot Rus equivalent section of wells Shawiya No.1 and Samawa No.1, respectively.

The 10 units of the Dammam Formation cover a territory exceeding 200 kilometers in width, in which they generally stand out as scarps and recognizable topographic features. They crop out in ascending se-

quence toward the east and trend generally north-northwest, almost parallel to the Euphrates River. Minor irregularities in this pattern are due to local topographic depressions such as those found in the As Salman and Ash Shabakah regions, where younger rocks have escaped erosion and thus occur in anomalous position.

Detailed lithologic description

In the reference section, the Dammam Formation consists of cream to gray limestones that are recrystallized, leached out (leaving a honeycomb appearance), very porous, and fossiliferous (abundant *Nummulites* spp.). Blue silty waxy shale streaks or partings occur toward the base; toward the top, the cream to gray limestone passes upward into dark-gray to black limestone, which in places is spotted by pyrite, is porous to fairly dense, and is variably recrystallized and dolomitized.

Because this formation crops out in the western desert in broad, flat-lying, and extensively denuded exposures, the width of which may exceed 200 kilometers, selection of one surface reference section is difficult; no measured thickness can convey the true thickness of the entire formation at one particular point. The great lengths of typical sections on the ground, the distances between sections, the possibility of lateral and vertical variations, and the possibilities of minor intraformational breaks and of extensive differential erosion of the various beds that make up this formation make thickness assessment very difficult. However, for the purpose of field studies, 10 distinct but informal units were recognized in the field. Their type sections are scattered throughout the territory, and their measured thicknesses are valid only for the representative sections; therefore, their cumulative thickness cannot be a measure of the true thickness for the Dammam Formation in any of the type sections, except perhaps by sheer coincidence.

The different beds, which generally stand out as scarps on the plain, crop out in ascending order eastward and in belts of variable width that, apart from the few exceptions previously mentioned, generally trend north-northwest. The lithologic descriptions of the informal field units, in ascending stratigraphic order, are as follows:

Wagha Beds: Limestone succession, white, chalky, intercalated with some yellow more marly beds, particularly in the lower few meters; thickness, 98 ft (23 m).

Sharaf Beds: Limestone, white and gray, saccharoidal, partly vuggy, fossiliferous, well-bedded, becoming massive bedded; recrystallized and siliceous with increase of quartz upward; weathers reddish brown and black toward top; thickness, 52 ft (16 m).

Shabicha Beds: Limestone, gray and white, recrystallized, massive, with thin-bedded intercalations; dense to vuggy; fossiliferous; chert nodules in upper half; weathers grayish brown; thickness, 131 ft (40 m).

Huweimi Beds: Limestone, white and gray, saccharoidal, vuggy, recrystallized, leached out, nummulitic, well-bedded, with sporadic thick to massive beds; thickness, 102 ft (31 m).

Shawiya Beds: Limestone, white, friable, detrital, succeeded upward by white siliceous nummulitic coarsely recrystallized hard limestone, which weathers red brown and black, thickness, 13 ft (4 m).

Chabd Beds: Limestone, white, soft in the upper part; well bedded with sporadic and local massive or thick beds; weathers gray; thickness, 39 ft (12 m).

Rudhuma Beds: Limestone, mainly gray and white, well-bedded, saccharoidal, some chert nodules; sporadically vuggy and recrystallized. According to H. Huber (unpub. data, 1944), this unit contains a thin bed of gypsum in vicinity of As Salman-As Samawah track near Faydat Ash Shaykh. This possibly indicates influence of the Rus Formation; thickness, 33 ft (10 m). Possible discontinuity between this unit and overlying Barbak unit in southern part of Galala "structure."

Barbak Beds: Limestone, white and gray, medium hard; some marly limestone incalculated with siliceous detrital material; also bryozoan and algal hard ringed limestone; weathers reddish brown and black; gray and brown chert nodules throughout; thickness, 61 ft (25 m).

Ghanimi Beds: Limestone, white, generally thin-bedded, some massive beds, especially toward base; includes dense to vuggy, commonly saccharoidal limestone; followed by soft leached out and friable saccharoidal limestones, some of which are highly siliceous and weather dark reddish brown and black; microbreccias and rare stringers of ballite and gypsum occur in the limestones, especially near Abu Khanzir; thickness, 52 ft (16 m).

Tuqaiyd Beds: Limestone, gray and white, massive, recrystallized, very hard, passing upward into white thin-bedded saccharoidal sporadically silicified limestones.

A number of these informal units were subsequently combined by R. M. Ramsden and C. A. Andre (unpub. data, 1953) into four informal units, as follows:

1. Tuqaiyd, Ghanimi, Barbak, and Rudhuma unit, consisting of bryozoan-peneroplid limestones and shelf limestones, with a rich fauna containing *Coskinolina balsillei* Davies, *Dictyoconus kohatensis* Davies, *Opertorbitalites douvillei* Nuttall, *Orbitolites complanatus* Lamarck, *Peneroplis damasini* Henson, *P. dusenburyi* Henson, *Præhapidionina huberi* Henson, *Rhapidionina urens* Henson, var. *minima* Henson, *R. williamsoni* Henson, *Somalina danieli* Henson var., and *Spirulina cylindracea* Lamarck.
2. Chabd, Shawiya and Huweimi (nummulitic) unit, consisting of nummulitic limestone containing *Alveolina elliptica* (Sowerby), *Dictyoconus kohatensis* Davies, *Halkyardia minima* (Liebus), *Nummulites discorbinus* (Schlotheim), *N. gizehensis* (Forskal), *Orbitolites complanatus* La-

marck, *Peneroplis dusenburyi* Henson, *Rhaphidionina urensis* Henson, *R. urensis* Henson var. *minima* Henson, and *Somalina danieli* Henson.

3. Huweimi (chalk), Shabicha and Sharaf unit, in which chalks alternate with chalky limestones that contain badly preserved lamellibranchs. The chalks are white or pink and have a fresh-water appearance.
4. Wagsa unit is a chalky, moderately fossiliferous limestone, with *Operculina libyca* Schwager occurring as a prominent fossil.

Attempts to correlate these field units with the subsurface Dammam Formation have been made by many geologists; however, none of their conclusions can be considered satisfactory because of lack of adequate information and study materials. A most plausible correlation was advanced by Bellen (Bellen and others, 1959). He stated that in the subsurface sections east of the area of outcrops, the base of the Dammam Formation contains middle Eocene fauna consisting of *Alveolina elliptica* (Sowerby), *Nummulites discorbis* (Schlotheim), *N. gizehensis* Forskal, and *N. lucasani* d'Archiac. This fauna occurs in the rocks that overlie the Rus Formation directly in the well sections but not in the base of the Dammam Formation in the field. There the basal limestones at the base of the Wagsa Beds contain a lower Eocene fauna with *Operculina libyca* Schwager. The Wagsa Beds in the field appear to lie unconformably on the Umm er Radhuma Formation without intervention of the Rus Formation. In well sections the middle Eocene fauna of the Dammam Formation occurs higher up in the limestone facies of the Huweimi Beds. We also may argue that the limestones containing *Operculina libyca* fauna of the surface exposures grade toward the offshore area into strata of the Rus Formation as found in the wells, and so does the second field unit of the Dammam Formation (Huweimi chalk, Shabicha, and Sharaf Beds) which has no apparent equivalent of Dammam Formation in the wells sections in which the Rus facies is developed. Bellen (Bellen and others, 1959) maintained that both the offshore facies were subsequently covered by the middle Eocene nummulitic limestones, which are normally found in the field at the base of the third unit of the Dammam Formation, the Huweimi (limestone), Shawiya, and Chabd Beds. This unit correlates very well with the base of the Dammam Formation in the wells. The above interpretation, advanced by Bellen, finds further support in the subsequently drilled wells of Samawa No.1, Shawiya No.1 and Ghalaian No.1. In Samawa well No.1 the sequence consists of the following three units:

Thickness
(feet)

3. Dolomite, buff, leached-out, vacuolar, and dolomitic limestones with gastropods and lamellibranchs at certain horizons -----	91
2. Limestone, white, recrystallized, locally chalky -----	90
1. Limestone, white, recrystallized, in places chalky and containing <i>Nummulites</i> spp -----	200

At Samawa well No.1 the Rus Formation itself comprises 245 feet of crystalline anhydrite with marl limestone and marl intercalations. A. Sayyab (unpub. data, 1960) considered this sequence to be very similar to that of other subsurface sections in the Al Basrah area, except for the absence of the upper bryozoan-unliolid limestone, which has possibly been eroded. Furthermore, the nummulitic facies of the above-mentioned unit No.1 which directly overlies the Rus Formation, according to H. A. Halliwell (unpub. data, 1962), can possibly be correlated with Huweimi (limestone), Shawiya, and Chabd Beds.

Farther west, in the wells Shawiya No.1 and Ghalaian No.1, which were spudded directly into the Huweimi (limestone), Shawiya, and Chabd Beds, the Rus Formation shows indication of gradual change of the facies. In Shawiya well No.1, stringers of anhydrite persist in an otherwise completely dolomitic limestone sequence with a thickness of 350 feet, but in Ghalaian well No.1 the facies change from evaporite to limestone seems to be complete where the evaporites have not been leached out. If this is true then it is another possible explanation for the absence of the Rus Formation in the surface sections. Bellen (Bellen and others, 1959) maintained that it is possible that percolating ground water may have removed the anhydrite, so that the apparent unconformity is not an original one. Facies change from Wagsa Beds and lower part of the Huweimi (chalk) Beds to Rus Formation remains a possibility because the correlation of upper Huweimi part of the Beds with the lower part of the Dammam Formation in the wells is probable.

Diagnostic fossils and age

The fossils contained in the rock samples from the reference section of the Dammam Formation are on the whole badly preserved; they include such forms as *Lockhartia huntii* Ovey var. *pustulosa* Smout and *Nummulites discorbis* (Schlotheim). However, a more numerous fauna determined from the surface and subsurface sections, includes algae, silicified wood, fish remains, ostracodes, lamellibranchs, *Meretrix* (*Cordopsis*) *incrassata* Sowerby, *Pecten* sp., *Ostrea* sp., *O. (Pycnodonta) brongiarti* Bronn., cf. *O. multicastrata* Deshayes, gastropods, echinoids, sponge spicules, bryozoans, *Alveolina* spp., *A. aff. elongata* d'Orbigny, *A.*

elliptica (Sowerby), *A. elliptica* (Sowerby) var. *nuttalli* Davies, *A. globosa*, *Articulina* sp., *A. iraqii* Henson, *Assilina* sp., *Bigennerina* sp., *B. cf. truncata* d'Orbigny, *Coskinolina* sp., *C. balsilliei* Davies, *Dictyonoides* spp., *D. kohaticus* Davies, *D. cooki*? (Carter), *Dictyonoceras* sp., *D. indicus*? Davies, *D. aegyptiensis*, *Discorbis* sp., *Halkyardia* sp., *H. minima* (Liebus), *Linderina* sp., *L. buranensis* Nuttall and Brighton, *L. brugesii*, *Lituola* sp., *Lituonella* sp., *Lockhartia* *tipperi* Davies, *Meandropsina* sp., miliolids, *Nummulites* spp., *N. beaumonti* d'Archiac and Haime, *N. discorbis*? Schlotheim, *N. gieschensis* (Forskal), *N. lucasanus* d'Archiac, *N. isubaticus* Douville, *Operculina* sp., *O. libyca* Schwager, *Opertorbitolites douvillei* Nuttall, *Orbitolites* spp., *O. complanatus* Lamarck, *Peneroplus* spp., *P. aff. carinatus*, *P. damesini* Henson, *P. duseburyi* Henson, *Prærhapidianina huberi* Henson, *Pyrgo* sp., *Rhapidianina* spp., *R. macfadyeni* ?Henson, *R. urensis* Henson, *R. urensis* Henson var. *minima* Henson, *Rhapidianina* sp., *R. williamsi* Henson, *Rotalia* sp., *Sakessaria* sp., Saudi sp., *S. discoidea* Henson, *Siderina* sp., *Sismondia* sp., *Somalina* sp., *S. danieli* Henson, *Spirolina* sp., *S. huberi* Henson, *S. cylindracea* Lamarck, *Textularia*, *Valvulina* sp., and *V. kitchini* Henson.

The Damman Formation is middle Eocene, according to Owen and Nasr (1958); however, absence of the upper Eocene has not been proved in Saudi Arabia (Sander, 1952; Steineke and others, 1958). Bellen (Bellen and others, 1959) maintained that the possibility of the base of the formation being late early Eocene cannot be excluded.

Contacts and equivalent units

The contact of the Damman Formation with the underlying Rus Formation is possibly a minor unconformity. There is slight indication of an unconformity between the Rus and the Damman Formations in well sections, where a gray-green shale approximately 7 feet (2.5 m) thick occurs near or at the base of the Damman (Bellen and others, 1959). No such unconformity is known to have been found in the field, but the lower part of the Huweimi (chalk) Beds contains white or pinkish chalks of fresh-water appearance (R. M. Ramsden and C. Andre, unpub. data, 1953). On the other hand, the upper part of the Huweimi (limestone) Beds is definitely representative of marine deposition.

Within these chalks of fresh-water appearance, however, are chalky limestones containing lamellibranchs. This disturbing fact has not been properly investigated in the field as yet. To date there is little reason to doubt the existence of a major facies change between lower and upper parts of the Huweimi Beds. In ex-

posures in western Iraq, the Wagsa Beds of the Damman Formation rest directly on the Unm er Radhuma Formation, presumably with unconformity.

The contact with the overlying Ghar Formation is unconformable. In the eastern sector of this area the Damman Formation is overlain transgressively with great unconformity by the younger units: Euphrates, Zahra, Lower Fars, and Dibdibba Formations, and Recent alluvium. The Zahra and Euphrates Formations rest directly on the Damman throughout an extensive sector in the northern part of the area.

The type locality of this formation is in Saudi Arabia at lat 26°17'03" N., long 50°07'07" E. The typical Damman extends into Kuwait. North and northeastward from the study region the formation passes laterally into the basinal Jaddala Formation (as in wells Awasil No.5, Ansal No.2, and Falluja No.1).

Economic aspects

Owen and Nasr (1958) stated that:

due to its natural porosity, enhanced by leaching of fossils, the Damman Formation is an excellent aquifer, and losses of circulation while drilling through this formation are a common occurrence. In Rumaila and Zubair fields, saline sulphurous waters are encountered. This is also the case in the Burgan-Magwa-Ahmad area of southeastern Kuwait. However, westward from Burgan the quality of the water progressively improves and in the vicinity of Abudha the Kuwait Oil Company has developed a supply of industrially usable water carrying some 3,700 ppm of total dissolved solids, some 1,400 ppm of calcium sulphate.

The Damman limestones cover an extensive part of western Iraq, including most of Al Hajara physiographic belt. A considerable number of wells have been dug and drilled in the area. Many of these wells reach into the Damman. Most of them are in surface depressions, or not far from the base of scarps, or in some wadi system. Macfadyen (1938) stated that:

A comparison of altitude and depth of water, taking into account so far as possible the topography and geological structure, does not appear to show any definite relationship between the water wells. Chemical analyses show wide variations, though the general type of water is, with few exceptions, similar throughout the area in both shallow and deep wells and springs.

It may be said with a measure of confidence that the evidence is sufficient to show that there is no true water table in the strong part of the southern desert, i.e., the Hajara, so that a well sited for convenience cannot be expected *a priori* to find water at any known depth. All ground-water supplies seem to be due to local accumulation of rainwater, and successful wells are those sited in or close to natural drainage lines, or in actual storage features, such as depressions with no outlet.

The water supply is thus in very direct relation to the rainfall, and in deep wells the supply is due to percolation downwards by means of fissures or solution holes, and storage in such cavities or in some porous horizon at depth. Thus, wells are best located in close relation to favourable surface features.

Faulting and folding appear to be rare in this desert, so that generally little help is available from the geological structure of the rocks. The varying quality of the waters, where this is not due to concentration by evaporation, is due to contact with more or less soluble constituents in the strata on its way down from the surface. The strata vary from place to place, and so give rise to some marked quantitative differences in the analyses of the waters in question.

MIocene AND Pliocene

The Miocene and Pliocene are represented by five formations having a maximum aggregate thickness of more than 3,350 feet. The stratigraphic correlation of the units is rather tentative because of lack of adequate information. The correlation adopted is that generally accepted by geologists of the Iraq Petroleum Company.

ZAHRA FORMATION

The Zahra Formation type section is in the small anticline that lies northwest of the depression Faydat Az Zahra, which lies 4.3 miles (7 km) south of Al Busayyah-As Salman track and 40 miles (65 km) west of Al Busayyah.

The Zahra Formation is 328 feet (100 m) thick at the type locality; elsewhere, the thickness of the formation is extremely variable, and it has a widespread but sporadic occurrence. Between the type locality and As Samawah, the Zahra Formation occurs as isolated outcrops on the Dammam Formation, predominantly occupying the old topographic depressions and former wadi floors. Typical outcrops are the Zahra outcrops of Shaib Abu Al Hazair, 30 kilometers southwest of 'Ayn Sā'i; Faydat Abu Sidaira and Shaib At Tayyar, 40 kilometers southwest of As Samawah; and Shaib Al Ash'ali, 10 kilometers west of Ayn Hamud.

To the west of this main belt of outcrop, in many topographic depressions, are beds that closely resemble the Zahra Formation. Examples occur in the As Salman group of depressions, such as Lahab and As Salman itself, where characteristic limestones and marls appear. Another good example occurs at Ash Shabakah (Shabicha) where the marls and limestones, lying on eroded surfaces, are slightly folded. Extensive outcrops can be found in Shaib Al Ghanimi between Al Burga and Ar Rimtha, on At Traq between Faydat Al Uba'id and Khashm and Dimana, and between Faydat Umm Jalib and Faydat Ar Rudhaima, Traq Al Galaib, and Ash Shawiyat. The Zahra beds may occur at any altitude in relation to the present drainage system. In the two last-mentioned localities, the beds cap some of the highest points of the two structures there, in places attaining altitudes of 20 to 30 meters above the valley floor, whereas in Ash Shabakah depressions the top of the exposed Zahra beds is in places as much as 30 meters lower than the Eocene

limestones. Northward from the type location, towards Galaib, the Zahra Formation thins considerably to only a few meters of white limestone. To the northeast, in the valley of the Shail Al Ghanimi, however, a thickness of more than 100 meters occurs in the normal facies of white limestones and red marls, indicating apparent eastward thickening. In the Zahra-Kabd (Chalad) area, eroded ridges of Dammam (Ghanimi and Chalad Beds) project through the Zahra beds which here commonly show false or exaggerated dips.

Along the southwestern Iraqi border, the Zahra Formation is extensive, commencing in the area of As Sadawiyat, 15 kilometers northwest of Nisab, and following the strip between Johka and Faydat al Batn and the border. In the region of Faydat Al Aghsas and Al Jumaima numerous inliers of Umm er Radhuma (Basita Beds) occur within the Zahra beds. The Zahra Formation extends into Saudi Arabia, near Birkat Al Amya, and reenters Iraq about 12 kilometers east of Al Lifiyah, where it continues northwestward rather irregularly. Farther north, it occupies the wadi floors of the Shaib Hisb, of Ghar as Saigal, and of Wadi al Khirr toward Al Lasaf; west of this line, and in the general area, it occurs as irregular patches, especially in the vicinity of Al Ashuriyah, Al Jamiliyah, and Bir Samit.

The Al Makim-Al Barrit-Al Lasaf region is extensively covered by Zahra beds containing numerous large inliers of Umm er Radhuma beds. The formation forms most of the gravel plain between Wadi al Ghadaf, Wadi al Ubayyid, and Wadi Tibal. It also covers part of the area west of Tar al Bahr. Westerly extensions of the formation occur in the Wadi 'Ar'ar, Wadi Hamir in the vicinity of Al Artawiya-Makhot, Shaib Ubaydat, east of Al Ubaydat, Shaib ash Shaykh, Wadi al Ubayyid, and Nukhaib; the formation extends farther north, where it covers the Habbariyah area.

Detailed lithologic description

The Zahra beds consist of gray, white, and red porcellaneous hard locally sandy limestones, which contain occasional *Chara*, fresh-water molluscs, and ostracodes and are interbedded with red sandy marl. Oblong cavities filled with a red sandy material are common in the limestones, especially in the west margin between Shaib Hisb and Wadi Al Khirr, and have been explained as being fossil cavities of roots of old reeds. According to T. F. Williamson and D. C. Roger (unpub. data, 1939), the formation as a whole becomes markedly thicker southward, until in the extreme south, near the Neutral Zone, it becomes a complete succession of grits and marls containing only a few thin fresh-water limestones. However, H. Huber (unpub.

data, 1944), is in favor of including the sands and grits in the locality near the Neutral Zone in the Dib-dibba Formation.

The succession may consist of strata of white and reddish-brown marls, sandy marls, sands, irregular pinkish-white chalky concretionary limestones, and conglomeratic or brecciated river deposits such as those at Saigal and As Salman.

In the Wadi Tibal and Wadi Al Ubayyid area the formation consists mostly of fresh-water limestones and coarse conglomeratic river deposits composed of recrystallized limestones of the Umm er Radhuma and Tayarat Formations.

Diagnostic fossils and age

Fossils in the Zahra Formation are rather rare; they occur mostly in the limestones and include *Chara* sp., *Melanoides tuberculata* Mueller, *Lymnaea*, *Planorbis* sp., *Vivipara*, and ostracodes. Some of the limestones show tubular holes probably made by reed stalks.

The age of this formation is still an open question, but opinion favors a Miocene (Fars) age. According to R. M. Ramsden and C. Andre (unpub. data, 1953), the formation overlies marls containing *Ostrea latimarginata* Vredenburg in the Shaib Hisb area; however, it could also be equivalent to the Euphrates Limestone, and thus be of early Miocene age.

Contacts and equivalent units in adjacent areas

The Zahra Formation may rest on any of the older units; the base of the type section is obscured by debris and cannot be seen, but a few kilometers to the southwest the white limestone beds rest on the brown Damman limestones.

In the As Salman area, H. Huber (unpub. data, 1944) found, at the base of the Zahra, a coarse-grained red sandstone, 13 meters thick, succeeded by well-bedded limestones containing sporadic marly intercalations. These bedded limestones contain numerous *Planorbis* sp., *Lymnaea* sp., *Ostracoda*, and *Chara*, but locally they may vary to gray cavernous limestones composed entirely of stalks and seeds of *Chara*. At Ukhaidir and in the Shaib Hisb the bedded limestones overly marls containing *Ostrea latimarginata* Vredenburg (indicative of Lower Fars), and near Takayyid (Tuqayyid) the Zahra Formation rests on a pebble bed which has been taken to represent the Ghar Formation. Along the southwest border of Iraq the Zahra rests unconformably on beds of either Umm er Radhuma or Damman Formation. The Zahra Formation unconformably underlies Recent gravels and sand in the Rudhuma-Chabd area. It may be partly equivalent to the Hofuf Formation of Saudi Arabia and may also

be equated with the Euphrates and Ghar Formations of southwestern Iraq.

EUPHRATES LIMESTONE FORMATION

Type and reference sections

The type section of the Euphrates Limestone Formation is near Wadi Fuhaime at lat 34°15'58" N., long 42°08'09" E., outside the study region. In southwestern Iraq, however, C. Andre and P. J. Walsmsley (unpub. data, 1952) referred to good exposures in Shaib Hish, 30 kilometers southwest of An Najaf; Wadi Al Muhari, southwest of As Shinafiyah and Sha'ib Firk (Firch); and Sha'ib Abū Maris, southwest of As Samawah. In the Al Busayyah area, a section just north of the Abu Ghar police post was described by T. F. Williamson and D. C. Rogers (unpub. data, 1939).

Thickness and extent

In the type section, which is outside of the study region, the thickness of the Euphrates Limestone Formation is only 26 feet (8 m). The Euphrates crops out over a wide area west of the Euphrates River where it overlies the older rocks transgressively, thus forming the eastern part of the western desert of Iraq, west of Karbala. The outcrop may exceed 100 kilometers in width. The Euphrates has a thickness of 15 meters in Wadi Al Ubayyid, less than 30 kilometers west of Qasr al Ukhaidhir; slightly south of Khan ar Runbah, it attains a 20-meter thickness. In this general area the width of outcrop decreases to about 50 kilometers, except for the few westerly isolated, scattered outliers. In the Kifl well No.1 the Euphrates-Jeribe Limestone Formation is 143 feet thick. These outcrops extend as far south as As Samawah, where they apparently disappear under the younger rocks; however, the Euphrates reappears farther south in the area of Makhfar (Shurtat) al Qusayr, from where it extends southwestward, swinging southward from the vicinity of Qal'at Abū Ghār, to an area south of Qulban Layyah, where the outcrop width may be as much as 50 kilometers. H. Huber (unpub. data, 1944) estimated a thickness of 30 to 35 meters for the Euphrates in the vicinity of Qal'at Abū Ghār.

Detailed lithologic description

In the type section the Euphrates Limestone Formation consists mainly of shelly, chalky well-bedded recrystallized limestones. West of Karbala the Euphrates consists chiefly of pseudo-colic generally soft marl-limestones, with chalky aspects and a few recrystallized bands.

In As Samawah and Makhfar Shurtat al Qusayr areas, the Euphrates consists of white limestones (some with pinkish tints) and marly, sandy limestones,

having a few siliceous intercalations and thick beds of loosely consolidated rounded sand, indicating the gradual influence of the Ghār clastics. Farther south this influence is strongly manifested in the section at a small hill just north of the Qa'at Abū Ghār police post, where the following section was described by T. F. Williamson and D. C. Rogers (unpub. data, 1939):

	Thickness (meters)
6. White, sandy, marly, fossiliferous limestone, with abundant lamellibranchs, <i>Clausinella</i> sp. -----	½
5. White calcareous grit -----	1
4. White calcareous marl grading into above -----	4
3. Pale greenish-white sand -----	4
2. White, sandy calcareous marls, slightly and locally ironstained -----	3
1. White marly limestone -----	½

South of Al Busayyah the Euphrates perhaps passes completely into the elastic Ghar Formation.

Diagnostic fossils and age

At the type section of the Euphrates Limestone Formation the following fossils were recognized: *Dendritina* sp., *Rotalia beccarii* Linn., miliolids, gastropods, lamellibranchs, and a rare Bryozoa, *Cellepora* sp. (Bellen and others, 1959).

In this area the fossils are rare and poorly preserved, they include a fauna of lamellibranchs—including *Clausinella* sp. and *Ostrea latimarginata* Vredenburg—and also gastropods and the foraminifer *Peneroplis farsensis*. The formation is early Miocene, according to Bellen (Bellen and others, 1959).

Contacts and equivalent units

In the type section the Euphrates Limestone Formation overlies the Oligocene Anah Limestone unconformably; however, in the southwestern desert this formation, being transgressive, overlaps older formations. The base of the Euphrates southwest of Karbala is a marked *Clausinella-lumachelle* horizon. In some places, the base is slightly conglomeratic, sandy, and commonly current bedded, as in the Sha'ib Abū Maris, or marly and chalky as at Shaib Hish. The Euphrates rests unconformably on the Ghanimi to Shawiya beds northwest of Shaib Hish, whereas to the southeast they may lie on the Ghanimi and Barbuk beds.

According to Bellen (Bellen and others, 1959), the Euphrates in the type area is covered by Jeribe Limestone Formation. In the western desert however, according to C. Andre and P. J. Walmsley (unpub. data, 1952), the Euphrates underlies the Lower Fars Formation and passes upward and laterally grades into it. The Lower Fars Formation west of the Karbala-An Najaf area is marked by a line of sabkha deposits along the west bank of the Euphrates River. It may

be directly overlain by the Dibdibba Formation, as in the area of Qulban Layyah.

The Euphrates Limestone Formation is equated with the Ghar Formation, which is considered to be the clastic facies of the Euphrates, and with the Serikagni Formation, which is considered to be the basinal facies of the Euphrates. The Zahra Formation may well be the fresh-water facies of the Euphrates. These relationships are rather complex and require verification by additional investigations.

Economic aspects

Water supplies.—Macfadyen (1938) pointed out the presence of a narrow and sharply defined zone of springs of economic importance along the east border of the southern desert. They lie mainly between the Euphrates and the overlying Lower Fars Formation and other younger formations, including the Recent alluvium. These springs include Ayn Ubaira, Ar Rah-hāliya group (lat 32°46' N., long 43°23' E.; alt 90 m above sea level), Ayn Fashash, Ayn al Bakhaiti, Ayn Zanga, Ayn Umm Shilla, Ayn Faidhia, Ayn Soda, Ayn ed Din (lat 32°41' N., long 43°23' E.), Ayn Umm al Khers (lat 32°37' N., long 43°26' E.), Shithatha group (lat 32°34' N., long 43°29' E.), Ayn Erbid, Ayn al Hamra, Ayn Abeid, Ayn Barkat, Khan ar Rahbah (lat 31°44' N., long 44°19' E.), Ayn Hassan, Ayn al Gayiani, and Ayn Seyid (lat 31°00' N., long 45°27' E.).

According to Macfadyen (1938),

The total of water from these springs is not less than 150 cusecs (425 centumecs), and this appears to be a permanent and invariable supply. It is very unequally distributed, over 100 cusecs (283 centumecs) being yielded by the Shithatha group alone, while other of the springs are very small.

The quality of the water varies slightly from spring to spring, but the analyses form a homogeneous group of saline water, characterized by moderately high magnesium, moderate calcium sulphate, high sodium chloride, and low carbonates. It is interesting to observe the approach of the Euphrates water towards this composition at the top water season in September. The springs often contain a little sulphurated hydrogen. The water is therefore not of the best quality, but it is drinkable and it is used extensively for irrigation of date and other fruit gardens. The temperature of water varies from 24° to 27°C, most springs being about 26°C.

These springs are replenished from rainfall in the southern desert that drains underground toward the Euphrates River, down both dip and slope; water of the Euphrates basin that makes its way southward along the strike of porous strata in the Euphrates limestone or lower fars beds; and, to a much lesser degree, by rainfall in the northeastern Iraqi mountains that makes its way beneath the Mesopotamian plain in the Euphrates Formation. (For further details see Macfadyen, 1938.)

Hydrocarbons.—Because the Euphrates Limestone Formation is extensively exposed in the area, the chance of finding accumulations of hydrocarbons in it is rather remote, though oil and gas in good quantities have been found in it elsewhere, as in the Jambur and Bai Hassan oil fields of northern Iraq.

GHR FORMATION

Type section, thickness, and extent

The type locality of the Ghar Formation is in BPC well Zubair No. 3, (lat 30°23'01" N., long 47°43'29" E., alt 51.9 ft; completed Feb. 21, 1951). The formation occurs between drilled depths of 1,513 and 1,935 feet. It is 422 feet (129 m) thick. This formation has been recognized in the Basrah Petroleum Company oil fields of Zubair and Rumaila, in Nahr Umr wells, and in the BPC wells Tuba No.1, Rachi No.1, Ratawi No.1, and Luhais No.1. In southern Iraq its thickness ranges between 300 and 500 feet; it shows thinning and change of facies eastward, northward, and westward by gradual passage to marly or silty sandstone. At Kifl well No.1 this interval is represented by the Jeribe limestone, whereas in the outcrop area it is possible that the Ghar sandstones pass into the Lower Fars marls and limestones and into the Euphrates limestones, which cover a considerable territory.

According to Owen and Nasr (1958), "the thickness of the Ghar Formation increases in a southwesterly direction towards what is believed to be the source area. Representative thicknesses in the southern Iraq fields are Nahr Umr No.1, 350 feet; Zubair No.3, 422 feet; and Rumaila No.7, 544 feet."

Detailed lithologic description

The Ghar Formation consists of: coarse sand, containing pink, black, and colorless gravel pebbles and locally having a calcareous cement; sandy limestone; marl; and streaks of gypsaceous blue clayey shale. In the outcrop area the entire Ghar formation seems to pass laterally into the Euphrates Limestone Formation, or it could be included with the Dibdibba Formation, in the absence of the intervening Lower Fars Formation, because of their close lithologic familiarities.

In this last respect Owen and Nasr (1958) stated, "that the division of the Kuwait Group into Dibdibba, Lower Fars, and Ghar Formations depends essentially on the presence of the Lower Fars beds, and where these are absent or only questionably developed, it has been found practically impossible to separate accurately the two clastic formations of the Dibdibba and Ghar. When this occurs, reference can usually be made only to the Kuwait Group."

The age of this formation is unknown, for fossils are absent, but it is considered to be early Miocene, though Owen and Nasr (1958) assigned to it an Oligocene and early Miocene age.

Contacts and equivalent units

The contact of the Ghar Formation with the underlying Dammam Formation is unconformable and is marked by the absence of proved Oligocene strata. The contact with the overlying Lower Fars Formation is gradational, without evidence of unconformity; in the absence of the intervening Lower Fars Formation, the Dibdibba Formation may overlie the Ghar Formation unconformably?, but it has been very difficult to recognize or separate them with great accuracy.

From stratigraphic considerations, the Ghar Formation seems to be equatable with the Hadhruth Formation of Saudi Arabia.

Economic aspects

Regarding the geologic occurrence of oil and gas in Iraq, the staff of the Iraq Petroleum Company (unpub. data, 1958) stated that very viscous sulfurous heavy oil (20° API) occurs in the lower limestone beds of the Lower Fars Formation, the upper Sands of the underlying Ghar Formation, and at Nahr Umr. This oil is locally called "First Pay."

LOWER FARS FORMATION

The heterogeneous Lower Fars Formation is the basal (evaporitic) division of Pilgrim's (1908) tripartite "Fars Series," according to Owen and Nasr (1958). The name Lower Fars was first published by Busk and Mayo (1918). In Iraq, equivalents of the Lower and Middle Fars were called the Hamrin Stage by Pascoe (1922), but the Middle Fars is so poorly developed outside Iran that it has long been included as an Upper Fars division, the term "Lower Fars" being arbitrarily used for the evaporitic Miocene below the highest bedded anhydrite.

Reference section, thickness, and extent

BPC well Nahr Umr No.1 (lat 30°45' N., long 47°40' E.; alt 21.5 ft) was completed Feb. 10, 1949; the Lower Fars Formation lies between drilled depths of 1,090 and 2,093 feet (1,003 ft thick). This formation has been found in the subsurface sections of the Basrah oil fields at Nahr Umr, Zubair, and Rumaila and at wells Tuba No.1, Ratawi No.1, Rachi No.1, and Luhais No.1. According to Owen and Nasr (1958) it ranges in thickness from 1,003 feet at Nahr Umr to 600 feet at Zubair and 300 feet at Rumaila. However, the thickness shows great local variations; for example, westward the thickness of Lower Fars at Luhais well No.1 is about 390 feet, and a similar thickness was

found at Kif well No.1, north of the area of present discussion. To the south in Kuwait the Lower Fars, according to Owen and Nasr (1958), is readily recognizable in the Kuwait Oil Company's well Raudhatain No.1 between drilled depths of 345 and 704 feet. Farther east in Kuwait, in the Jal-es-Zor escarpment along the north side of Kuwait Bay, is a 125-foot unit of Lower Fars equivalent. In the western desert this formation crops out in the area of Qasr Shaqrah, Dafina, Qasr Naba, Qasr Abu Ghar, Al Busayyah, Al Buwaib, and Khashmat ibn Hallaf. Isolated outliers of the Lower Fars lying above the Euphrates occur at Sha'ib Abū Maris, 30-35 kilometers west and southwest of As Samawah. Farther north, outliers of Lower Fars Formation are found at Al Muhair and Quwairat al Habbusa, southwest of As Shinafiyyah, and at Khan ar Rahbah and Qarat as Saba. Extensive outcrops spread west of An Najaf in the area around Az Zigla and Gur al Hibari.

In the Gur al Hibari area the Lower Fars Formation has been subdivided into two units; the lower is yellow limestone with some white chalk bands and green and red marls, and the upper is selenite. The lower unit is considered to be much more persistent. In the Qasr al Ukhaidir area the thickness of the lower unit does not exceed 130 feet, and the width of continuous outcrop is not great, but outlying hills of it occur almost as far west as the Nukhaib police post, some 130 kilometers west of where the formation disappears under the overlying sandstones and marls. As for the upper unit, T. F. Williamson and D. C. Rogers (unpub. data, 1939), after a study of the north-trending cliff which passes east of the Bahr al Milh, maintained that the sequence is a lateral variant of the basal small section of the Upper Fars Formation; this is clearly exhibited at the Nuqtah Cliff section on the track between Shithatha and Karbala where the basal beds of the Upper Fars Formation contain much crystalline selenite. Northward these beds show such an increase of gypsum that 15 kilometers northwest of the Tazaza village, distinct white beds of selenite can be distinguished. These attain thicknesses of as much as 5 feet (1½ m) and stand out as hard bands among marls and a sandstone sequence. South of the Shithatha-Karbala track only the lower unit is recognizable. It forms numerous outliers in the area of Wadi al Ubayyid. Even along the base of the scarp toward An Najaf there is comparatively little continuous outcrop. Here the formation dips gently to the northeast, with the result that only a few isolated outliers of limestones and green

marls can be seen resting on the Euphrates Limestone Formation. These are present in the low ground from near the Euphrates river to As Samawah, beyond which there are practically no further occurrences until the group emerges again from the sabkhas near Makhfar al Qusayr. From here southward the Lower Fars appears to be insignificant, and its name has, for the sake of uniformity, been applied to the rather marly fossiliferous beds above the Euphrates and below the more definitely sandy beds of the Upper Fars and Dibdibba Formations. In places the Lower Fars is very thin. It consists mainly of greenish marls with abundant selenite crystals, and sporadic "oyster beds" occur containing very numerous *Ostrea latimarginata* Vredenburg, pectens, and *Clausinella* sp. One good example of these "oyster beds" can be seen just west of the track from Al Busayyah to An Nasiriyah at a point about 10 kilometers north of Qasr Naba. At Al Busayyah, Laiyah, and farther south, the grits and marls rest directly on the Euphrates Limestone Formation.

Detailed lithologic description

The Lower Fars Formation is an evaporitic sequence; it comprises the lithologic units given below:

	Thickness (feet)
4. Mudstone, gray and red, with subordinate streaks of nodular gypsum; some red-blue marl and loamy grit.	258
3. Limestone, buff, sandy, porous, shelly, fossiliferous (<i>Clausinella</i>), in part oolitic or cherty and porcellaneous, alternating with gray clayey mudstones, shales, marls, and rare streaks of selenite.	321
2. Selenite beds alternating with gray-blue mudstones and brown-blue marls.	249
1. Limestone, pinkish-white, sandy, in part oolitic or very shelly, recrystallized with rare streaks of blue mudstone especially toward base.	175

To the south, in Kuwait, the Lower Fars consists mainly of anhydrites, gypsum, clays, marls, and shallow-water limestones containing *Ostrea latimarginata*, *Clausinella* sp., and *Quinqueloculina* sp. Farther south into Kuwait, in the Jal-es-Zor escarpment along the north side of Kuwait Bay, there is a 125-foot unit of fine-grained sand, silt, and clay carrying *Ostrea latimarginata*, *O. vestita*, lamellibranchs, and other fossil forms. This unit is locally called the Zor Formation.

According to T. F. Williamson and D. C. Rogers (unpub. data, 1939), the thickness of the Lower Fars Formation in this southwestern region is insignificant in comparison with that attained in the Iranian and north Iraqi foothills.

Westward from the Euphrates River, the Lower Fars Formation becomes generally and gradually less

evaporitic and passes into clastic sedimentary rocks laterally and vertically.

Diagnostic fossils and age

The fossils of the Lower Fars Formation include *Ostrea latimarginata* Vredenburg, *Clausinella* sp., peccens, gastropods, *Quinqueloculina* sp. and other miliolids, ostracodes, and other forms. Owens and Nasr (1958) considered the age of this formation to range from early to middle Miocene.

Contacts and equivalent units

The underlying contact of the Lower Fars Formation with the Ghar Formation is conformable and gradational in the Basrah area; in the Karbala, An Najaf, and As Samawah areas the Lower Fars Formation overlies the Euphrates Limestone Formation conformably.

The contact with the overlying Dibdibba Formation is gradational (Owen and Nasr 1958). Northward, the Upper Fars replaces the Dibdibba Formation gradually. Here the Lower Fars Formation is considered as being equivalent to the Dam Formation in Saudi Arabia and the Zor Formation in Kuwait.

Economic aspects

In the Basrah area the basal limestones of the Lower Fars Formation and the upper sandstones of the Ghar Formation generally contain very viscous sulfurous heavy oil (20° API). The two zones constitute what is called the "First Pay." The Lower Fars anhydrites and shale can act as caprock under favorable circumstances for the accumulation of oil.

DIBDIBBA FORMATION

Reference section, thickness, and extent

Macfadyen (1938) mentioned Birjisiya (lat 30°22' N., long 47°38' E.) as the type locality for the Dibdibba Formation. Since his account, however, the thickness of the material exposed in the hand-dug water well at Birjisiya has been far exceeded in nearby Zubair, where numerous wells of the Basrah Petroleum Company have penetrated deeper than 1,000 feet (305 m). Owens and Nasr (1958) did not specify a type locality but merely mentioned the presence of the Dibdibba Formation at the surface and in all drilled wells on the Dibdibba plain. In the BPC well Zubair No. 3 this formation lies between the ground surface and a drilled depth of 935 feet.

It is as much as 1,160 feet (354 m) thick in the northernmost wells of the Zubair oil field. The formation has extensive distribution in southern Iraq, for it covers the area between the Shatt al Arab River in the east and Haur al Hammar and the Euphrates

River in the north. Westward, the outcrop trends from Tall al Muqaiyir Dafina, Qasr Shaqrah, to Al Amghar, where it extends farther west to Jan Khirsan, Al Buwaib, Adam, Abu Radham, Tukayyid, and the Neutral Zone. Southward, it extends into Kuwait and Saudi Arabia. The region covered by this formation is known as Ad Dibdibba.

This formation shows gradual decrease in thickness westward. In the Rumaila field it decreases to some 500 feet; farther west, to about 160 feet in the vicinity of Luhais well No.1. Northeast of Abu Ghar, a thickness of 196.8 feet (60 m) has been noted. Still farther west the formation disappears completely. According to Dunington (1958), "thinning takes place also towards the south where over 700 feet (243 metres) occur in the southern wells of the Zubair oil field." Northward and eastward this formation disappears under the Recent alluvium.

Northward, the Dibdibba Formation passes into the Upper Fars Formation which crops out as a scarp between Ur Junction and Al Shararain. Here the Upper Fars consists of about 8 meters of sandy marl containing selenite, which dips gently to the northeast. These marls are practically surrounded by sabkha. Farther northwest, in the sandhills south of As Samawah, the few Upper Fars sandstone inliers outcrop from the sabkha. To the southeast of An Najaf, very little is seen of this formation, as the Lower Fars Formation extends under the recent deposits of the Euphrates River valley. A thickness of at least 154 feet (50 m) for this formation was measured by T. F. Williamson and D. C. Rogers (unpub. data 1939) in the scarp east of Ukhaidhir. Farther north, this formation forms the prominent scarp, which overlooks the Bahr al Milh and Abu Dibs from the east, and extends eastward toward the Euphrates. The cliff extends south-southwest and then turns sharply to the east to An Najaf. The base of the formation follows roughly the line of the foot of the cliff. In this area it comprises a series of brown, red, yellow, and green marls containing some sandstone bands and, at the base, some disseminated selenite crystals.

Detailed lithologic description

The composition of the Dibdibba Formation is, "mainly sand and gravel of igneous rocks, including pink granite, various liver-coloured and slate-grey intrusives, dolerites, etc., and white quartz pebbles. Not infrequently the rock is cemented to a hard grit." (Macfadyen, 1938).

Similar lithological sequence occurs in the subsurface sections of the Zubair field where the Dibdibba

Formation consists chiefly of coarse sands grading into gravel with subordinate arenaceous limestone beds and gypsum streaks.

In the northern part of the Dibdibba area, in a low ridge southwest of Un Junction, coarse- and medium-grained Upper Fars sandstones grade southward into the pebbly Dibdibba Formation.

Between the Tukayyid scarp, Jalib Al Amghar, and the north tip of the Neutral Zone, a great thickness of pebbly sandstones, grits, and fresh-water limestones occurs. H. Huber (unpub. data, 1940) included in the Dibdibba Formation the loose sands and loosely cemented sandstones that occur in the depression between the Tukayyid (At Traq) scarp and the Neutral Zone and the Eocene beds in the west. In these sandstones Huber observed some pebbly beds. In several places along the Tukayyid scarp from Khashmat al Masasah to Jalib Al Amghar, as well as along the north boundary of the Neutral Zone, the Dibdibba sandstones and grits contain intercalations of fresh-water limestones. Some of the limestones, especially to the west of the Tukayyid well, are dark greenish brown and contain coarse rounded sand. The limestones are well bedded (+0.20 m) and very hard and contain *Chara* sp., *Planorbis* sp., and *Radix*.

Several small hills in the vicinity of the Tukayyid well are composed of a bedded, at places sandy, dense gray and white limestone; at many places it shows reddish tints and contains remains of *Chara*. Some dark gray thick-bedded hard limestones containing *Chara* also occur. Between this well and Al Karatha, similar *Chara*, bearing limestones are interbedded with sandstones and grits on top of the scarp along the track leading to Jalib Al Amghar and to Maghaizil and along the northwest border of the Neutral Zone. Some conglomerates occur in the vicinity of Ad Dayir.

R. M. Ramsden and C. Andre (unpub. data, 1953) stated that the exposed part of this formation can be divided in ascending order, into two recognizable units: Chilawa Sandstone and Rafaiya Gravel.

Chilawa Sandstone.—The Chilawa Sandstone consists of bedded unfossiliferous sandstones and grits. A type section at Chilawa near triangulation point 130 m (coordinates 1.672,401.44 E.; 88.7,596.94 N.) exposes approximately 180.4 feet (55 m) of gritty white, pink, and green sandstone. The white sandstones have a calcareous cement and form terraces and erosional plains. The pink sandstones are softer than the white and probably contain some calcium sulfate and grains of sulfur. The green sandstones are generally uncemented and slightly marly. Small brown quartz pebbles are scattered

throughout the section. This unit forms the upper part of the Al Busayyah-Qasr Shawrah scarp and passes eastward across the Dhafir plains to the Boliya axis. The exposures can be seen in the scarps at Twai al Hashash, Khabra or Rachi, and Jarishan to the south. The unit can also be found dispersed along and adjacent to the Al Basrah-Jalibra track, north and south of Hawr al Hammar, where it forms the main exposed part of the Dibdibba Formation.

Rafaiya Gravel.—The Rafaiya Gravel is thick in the area between the Boliya axis and the west flank of the Zubair anticline, where it forms a layer of well-rounded exotic pebbles. These pebbles are composed of igneous, metamorphic, sedimentary, and conglomeratic rocks, the character and source of which have not yet been investigated in detail. Individual cobbles may be as large as 15 centimeters in diameter. The lateral and vertical limits of this unit are difficult to define in the east. To the west the gravel is not found west of the Boliya axis, perhaps in part because of erosion. At Boliya it forms a single layer of pebbles overlying gypsaceous and sandy earth which is a few feet thick. At Rafaiya (grid coordinates 1732 E., 932 N.) the type section of the unit, moderately coarse gravel lies at the surface; the pebble layers can also be found in the walls of the large waterhole. In the south, extensive tracts of coarse gravel, mainly quartz, are found in the Adnan region. The true correlation of these still remains to be decided.

Diagnostic fossils and age

Ostracodes, *Chara* sp., *Planorbis* sp., and *Radix* are found in the Dibdibba Formation in isolated surface limestones in places west of Basrah, and according to Hudson and others (1957) their age is not known. Dunnington, Wetzel, and Morton (in Bellen and others, 1959) stated, "This formation probably ranges from 'late' Miocene through Pliocene to early Pleistocene, but no fossil evidence has been produced to support or add precision to this range." On the age of Dibdibba Formation Hudson and others (1957) wrote, "Direct evidence of age is not available; comparison with other areas in the Middle East suggests that the Dibdibba Formation is late Miocene or Miocene and Pliocene."

Contacts and equivalent units

The contact of the Dibdibba Formation with the underlying Lower Fars Formation is conformable and gradational. The Upper Fars Formation has not been recognized in the subsurface sections of southern Iraq, where equivalents are probably included within the lower parts of the Dibdibba Formation. Wherever the Lower Fars Formation shows a change of facies into

a clastic type, the differentiation of it from either the overlying Dibdibba Formation or the underlying Ghar Formation is very difficult. In the western outcrops, according to T. F. Williamson and D. C. Rogers (unpub. data, 1939), the Dibdibba Formation overlies the Euphrates Limestone Formation and the Lower Fars Formation. In the extreme southwest where the Dibdibba cannot readily be distinguished from the clastic variant of Lower Fars, if present, or from Ghar Formation, it rests unconformably with great overlap on the Damnam Formation.

The Hammar Formation and Quaternary gravels and alluvium overlie the Dibdibba; the contact is unconformable. Hudson and others (1957) stated:

The solid rock underlying the Mesopotamian plain and outcropping west of Hawr Al Hammar is that of the Dibdibba Formation (Macfadyen, 1938, p. 103; Mitchell, 1956, p. 400). This succession is of sand and pebble beds, often cross-bedded, occasionally calcareous or gypsiferous and cemented, and with some silt and clay. To the west of Zubair the Dibdibba beds are capped by pebbles and boulder beds of igneous, metamorphic, or sedimentary rocks, . . . [and] above these older rocks there is a surprisingly small thickness, rarely exceeding 100 feet, of unconsolidated Recent sediments, in which the succession seems to be fairly constant, being one of marine beds, followed by alluvium, variously estuarine, lacustrine, or fluvial. The marine beds are here called the Hammar Formation.

In southern Iraq the Dibdibba Formation is considered to grade eastward and northward into Upper Fars Formation and the Bakhtiari Group beneath the Mesopotamian Alluvia and to crop out in central, eastern, and northern Iraq as distinctly recognizable units. The equivalent of this formation in Saudi Arabia may be found as gravel and sandstone in the Hofuf Formation.

Economic aspects

The Dibdibba Formation comprises gravels and coarse-grained sandstones which can make a good aquifer. In the Dibdibba region of southern Iraq the water supply is chiefly dependent on the rainfall; owing to the high porosity of the Dibdibba sandstone and sands, much of the water may sink into the ground and be stored or may drain into local surface depressions in which some water gradually percolates into the ground and some evaporates. The underground drainage is toward the Euphrates and Shatt al Arab Rivers, down both dip and topographic slope. The movement of the ground water in the Dibdibba region will certainly be affected and influenced by the general ground water of the Mesopotamian basin. (See Macfadyen, 1938.) Water in great quantities can be found stored in this formation, but its quality may be highly variable.

The gravelly components of the formation locally are manually collected and sold for concrete aggregates and for surfacing the roads.

QUATERNARY

The Quaternary is represented by Pleistocene and Recent (Holocene) sediments, which may not exceed 300 feet in thickness. The marine Hammar Formation only has been described below. The top of the Recent sediments in the area is constantly acted upon by factors of current denudation or deposition.

HAMMAR FORMATION

TYPE SECTION, THICKNESS, AND EXTENT

The type section of the Hammar Formation is in BPC well Zubair No. 31 (lat 30°31'00" N., long 47°36'34" E.; alt 20.3 ft, completed Oct. 24, 1953) between 20 and 41 feet of drilled depth. The formation is 21 feet thick. This Recent marine formation occurs in the subsurface sections on the southern limits of Hawr al Hammar in the northern sector of the Zubair oil field, where the type section is located.

Eastward across the Shatt al Arab, north of Bandar Shapur, Thomas (in Lees and Falcon, 1952) reported a succession of marine shelly silts overlain by fresh- or brackish-water silts containing ostracodes. The brackish-water silts total at least 20 feet in thickness, and the lower marine silts are possibly 60 feet thick. On the northeast side of Hawr Al Hammar, this formation was found in the Nahr Umr wells, close to the Shatt al Arab, where it consists of 32 feet of shell marl containing lamellibranchs, gastropods, bryozoans, and other forms in a fauna almost identical with that of the Hammar Formation in the type section. According to Hudson and others (1957), this formation extends as far south as Al Faw (Fao), in the extreme south of Iraq, where a number of water wells were drilled in soft silts to a depth of 30 feet. They stated that "the general succession was one of a lower marine silt with abundant shells and an upper silt with ostracodes and occasional crab debris, probably estuarine. There was a slight difference between the succession in the various wells, the greatest thickness of the estuarine silt being 20 feet (well No.3) and that of the marine silts being 30 feet (well No.2)." The fauna of the marine silts is that of the Hammar Formation.

The only evidence of the northward extension of this formation, according to Hudson and others (1957), is that of W. A. Macfadyen (in Lees and Falcon, 1952) who reported 35 feet of alluvium with marine Foraminifera at Al Amarah, 95 miles north-northwest of Al Basrah. Mitchell (1958) discovered a Recent marine fauna near An Najaf at altitudes of 40.7 to 41.3 meters above present sea level.

DETAILED LITHOLOGIC DESCRIPTION

In the type section the Hammar Formation consists of two main units:

- | | Thickness
(feet) |
|---|---------------------|
| 2. Clay, gray, with thin washes of shells consisting predominantly of <i>Abra cadabra</i> ; local crab debris; the lowest foot consists of shell marl containing an abundant and varied fauna, including abundant echinoid debris | 7 |
| 1. Sand, coarse and very coarse, poorly graded, rarely cemented, and some silt; some of the sand is wind-blown; abundant small shells of marine organisms concentrated in thin bands and washes | 14 |

DIAGNOSTIC FOSSILS AND AGE

The Hammar Formation is of Recent age. Its fauna was described fully by Hudson and others (1957), who stated that:

The common fossils, in order, are: Lamellibranchs—*Pitar becheri*, *Brachidontes variabilis*, *Corbula sulculosa*, *Abra cadabra*; Gastropods—*Minolia adyma*, *Hinia idyllia*. The forms identified are listed below:

Gastropoda *Anachis* (*Zafra*) *melatoma* (Melvill and Standen), *Calyptrocha chinensis* (Linne), *Cerithium amirantium* E. A. Smith, *Chrysalidia callista* (Melvill) *Chrysalidia tenax* Eames and Wilkins, *Crassispira* (*Clathrodorilla*) *lucida* (G. and H. Nevill), *Cuma corinifera* (Lamarck), *Cyclostrema supremum* Melvill, *Fossarus stolicekanus* Nevill, *Gemma multiseriata* (E. A. Smith), *Gibberula* (*Cyrtus*) *mazagonica* (Melvill), *Hammarilla bicarinata* Eames and Wilkins, *Hinia idyllia* (Melvill and Standen), *Leionardia soror* (E. A. Smith), *Mangelia pelyi* (E. A. Smith), *Meloceras* sp. *Melanella* (*Polypirculima*) *brevitata* (H. and A. Adams), *Minolia adyma* Melvill, *Mitrella blanda* (G. B. Sowerby), *Natloa* (*Cochlis*) *tranquilla* Melvill and Standen, *Oblortio* (*Alabina*) (*Fenella*) *purpureopiscata* (Preston), *Odotostoma eutropia* Melvill, *Pyrunculus abbreviatus* Eames and Wilkins, *Reisus inconspicua* (A. Adams), *Retusa*? *Siphonium cf. maximum* (G. B. Sowerby), *Stenothyra minima* (G. B. Sowerby), *Strioterebrum* (*Noditerebra*) *edgari* (Melvill), *Triphora acuta* (Klener), *Turbonilla* (*Chemnitzia*) *galactodes* Melvill, *Turritella terrebra* Lamarck.

Lamellibranchia: *Abra cadabra* Eames and Wilkins, *Abra Tellina*, *Barbatia fusca* (Bruguiere), *Brachidontes variabilis* (Krauss), *Corbula sulculosa* A. Adams, *Cuma cori* Eames and Wilkins, *Leionucula layardi* (A. Adams), *Mastra olivina* Philippi, *Ostrea*?, *Pholas mantiducula* Philippi, *Pitar becheri* (G. B. Sowerby), *Piacuna*, *Tellina* (*Pammotaca*) *methoria* Melvill, *Tellina*, *Yoldia tropica* Melvill.

Scaphopoda: *Dentalium quadrangulatum* G. B. Sowerby, *Dentalium*.

Bryozoa: *Acanthodesia sacarii* (Audouin), *Mucronella triplicosa* (Johnston), *Mucronella*?

Anthozoa: *Paracystothus* sp. nov., corals indet., Pennatulacea. *Cirripedia*: *Balanus*.

Decapoda: *Callinassa* sp. nov., crab fragments, echinoid plates and radiolites.

The fauna of the Hammar formation is without doubt of Recent age, all forms existing in the present seas, some of them now living in the shallow coastal waters of the Red Sea, Trucial Coast, Oman Coast, and Persian Gulf.

CONTACTS AND EQUIVALENT UNITS

The Hammar Formation is underlain, probably unconformably, by the Dibdibba Formation. It is overlain by Recent lacustrine or estuarine alluvium which consists of 20 feet of buff and red silt and some sand and pebbles. The top 3 feet of the alluvium contains abundant salt and gypsum crystals. Toward the middle the silt contains the brackish-water ostracodes *Cyprideis litoralis* (Brady) and, more rarely, *Limnocythere*. Thus, the silt is considered as estuarine and the remainder of the alluvium as fluvial or lacustrine.

The equivalents of this Recent marine formation are expected along the coastal line of Arabia and over Arabia to be manifested in different and highly variable lithologic and facies forms.

ECONOMIC ASPECTS

No economic value has so far been attributed to the Hammar Formation, although some of the higher parts in the Recent alluvium that are scattered along the highway between Al Basrah and Al Amarah have been utilized for brick making in the Brick Kiluf.

STRUCTURE

STRUCTURAL PROVINCE OF SOUTHWESTERN IRAQ

Iraq, in general both geologically and geographically, has been influenced by the proximity of the Precambrian Arabian shield (Furon, 1963) and the Zagros province of the Tethyan geosyncline. Tectonically, it can be subdivided into three major interrelated units, each with its distinct and characteristic tectonics and geologic history. These units from northeast to southwest are: (1) the major and complex overthrust or "nappe" belt, (2) the autochthonous folded belt, and (3) the unfolded area (Dunnington, 1958; Naqib, 1960).

An elaborate analysis of the tectonic construction of the Middle East in general, including northern Iraq, has been made by Henson (1951), who stressed the important role played by pre-Miocene vertical movements in the unfolded area and in the folded zone. Henson considered that folding due to late Tertiary compression was superimposed on and molded against an earlier deep-seated block-faulted framework, inherited from the pre-Miocene history of the region. Other accounts by Boeckh and Viennot (1929), Lees and Richardson (1940), and Lees (1950a, b, 1951, 1953) have accepted uncomplicated compressional folding, with a broad "normally folded zone" intervening between the "nappe front" and the unfolded "foreland."

A rather different quadripartite subdivision was introduced by Mitchell (1959), who included Iraq in (1) the Stable Shelf, (2) the buckled Labile Shelf of the Foreland, (3) the autochthonous border folds, and (4) the Iranides of his Orthogeosynclines of southwest Asia.

The tripartite division into unfolded, folded, and "nappe" zones, on the dominantly northwest-southeast trend of the Zagros, is appropriate for post-Miocene time and is harmonious with existing concepts of a Cretaceous and Pliocene geosyncline developing on the same Zagros trend, with its axis migrating more or less progressively southwestward until the orogeny in Pliocene time. Conditions in Jurassic and pre-Jurassic time were somewhat different. The basinal trend ran more nearly north to south than northwest to southeast in the known Jurassic stages, and the Jurassic and Cretaceous transition was probably a time of tectonic disturbance, including widespread uplift and tilting of fault-bounded blocks on the west margins of the basin. Several deduced faults of this age are directed north to south, across the Zagros trend. The axes of thickest basinal deposition for the Jurassic stages underlie thin accumulations of shallow-water Lower Cretaceous sediments. Figure (1) shows the major tectonic zones of Iraq and their characteristic elements.

The "nappe" zone is confined to a narrow belt in the remote northeastern part of Iraq and consists of an area of highly complex tectonics featured in extensive overthrusts; the rocks generally show some low-grade regional metamorphism (slates, phyllites, and schists). The area has undergone extensive igneous activity, including extrusion of basalt, spilite, and andesite, accompanied by some explosive volcanism, evidenced by pyroclastics and tuffs and also by intrusion of dolerite, mafic rocks, and granite. The topography of this area contrasts sharply with that of the simple-fold mountainous country of the zone of autochthonous folding farther southwest. It follows a surprisingly linear northwest-southeast trend from Rayat in northern Iraq to Bandar Abbas in southwestern Iraq.

The second unit forms a wider belt that extends in a general northwest direction in the northeastern part of Iraq and falls into three arcuate segments that bulge southwestward. This zone has an average width of about 100 miles (160 km), and the alignments of individual folds and the belt itself follow the Zagros swing from east-west in the north to northwest-southeast in the south. The segments of the autochthonous folded belt have been overridden by the linearly trending overthrust belt (Gansser, 1955) in the northeast as if they had differential lateral displacement along lines of

crustal weakness perhaps with north-south Caledonian trend.

The boundary between the folded and unfolded zones is abrupt. The southernmost and westernmost anticlines of the folded zone—Jebels Sinjar, Sheikh Ibrahim, Sadid, Makhul, and Hamrin North and Hamrin South—are surprisingly large folds, tens of miles long, and in some places rise several thousands of feet out of the adjacent synclines. The boundary follows a more or less arcuate line, from northwest-southeast in the southeast to east-west in the northwest, but it is offset sharply in the area west of Qaiyarah. Here its course is picked out by the north-south alignment of the pitching ends of five rather small and low anticlines. The line plunges below alluvium in the plains east of Bagdad or is offset northward, near Naft Khaneh, to the foot of the exposed Iraq-Iran frontier folds.

In this unit the anticlinal folds are simple and sharp, generally without faulting and subordinate thrusting. The structures are en echelon and are separated by broad synclines. In this zone, the intensity of folding, as reflected in the magnitude of the amplitude of the fold system, diminishes gradually southwestward from the region of high complexity in the northeast to a stable and tectonically undisturbed zone in the west. Thus, indeed, according to Dunnington (1958), there is an overall tendency for anticlines to increase in amplitude and tightness as the "nappe front" is approached, the most northeasterly folds being themselves thrust and locally overturned. There are, however, many departures from the superficially natural expectation that the folds should diminish in strength with increasing distance from the thrust front. Thus, Hamrin North, Makhul, and Sinjar are much more developed and much more elevated than the anticlines that occur immediately to the north and northeast, whereas flat, low domes appear between steep, narrow neighboring anticlines in the middle of the zone. Other oddities include the great elevational differences between adjacent anticlines of otherwise similar dimensions, the pitching down of successive anticlines along linear features, and the appearance of marked asymmetry in some folds and of opposed asymmetry in some pairs of adjacent folds. These and other anomalies substantiate the opinion of Henson (1951) that the late Tertiary folding in the folded zone was intimately affected by a preexisting complex of faults, which left residual features to buttress or deflect folding and which predisposed the region to react in irregular and complex fashion to simple tangential pressures.

The unfolded zone includes an extensive area of central, southern, and western Iraq; the Jebels Sinjar,

Makhul, and Hamrin mark the northern and eastern limits. The present discussion covers only the southwestern part of this area. The structural unit itself is characterized by relative absence of surface structural features except for a few folds of small amplitude and structural depressions many of which may be of only superficial origin.

In the unfolded zone, but northwest of the area discussed, a single broad dome with an east-west alignment occurs in the Ga'ara depression north of the Wadi Hauran. This dome, which exposes Lower Triassic (?) rocks in its center, is on the flank of a very broad uplift, which may reflect basement arching. Farther north, a second prominent east-west fold, narrow but gentle, is known at Anah on the Euphrates; its fault-trough setting strongly indicates a fault origin for the anticline itself. Gentle folds may occur between the Tigris and Euphrates Rivers in front of the autochthonously folded zone under the flat-lying Pliocene, Pleistocene, and Recent sediments. A few minor folds, trending northwest, occur in the neighborhood of Hit and Ramadi.

The unfolded area considered falls within the Interior Homocline of the Arabian tectonic framework defined by Aramco geologists. Here, with the exception of the Miocene and post-Miocene rock units, exposures of rocks from the Cretaceous System upward shift east in almost parallel strips, and their structural features appear in general to be of the simplest nature. They are almost flat over wide areas, with slight dip, measureable only in a few meters per kilometer, toward the east or northeast. The salient features of the area are Jabal Sanam in the Basrah area, depressions which may be structural basins, and some disturbed scarps. The structural profile across the area (pl. 4) portrays the general structural relationships of the different systems in surface and subsurface. At the surface the Cretaceous exposures do not convey any impression of diastrophism.

The Batn-Ghurra escarpment of Paleocene and lower Eocene (?) rocks is irregular and roughly aligned in a north-northwest direction. It is extensive and variable with uncertain origin. In the Al Makmin (Machi) area it shows slight sagging. The Batn scarp in general has a very gentle east dip, and in certain places (for example, Lifiya) it consists of a simple typical erosional scarp with folded Basita Beds about 2 kilometers to the west. Reversals in dip over the scarp can be seen in places, for example near 'Aydaḥā, where closely folded beds occur more than 1 kilometer west of the scarp. In many places, beds of the Zahra Formation are also involved in local folding.

The Waqisah scarp in the area of Al Jill-Wagish, according to F. J. Venn (unpub. data, 1957), is of erosional origin. It shows well-bedded horizontal limestones commonly with more than one scarp because of differential erosion. They show no "draping" toward the foot of the scarp except for occasional but random collapse of the scarp edges.

The At Traq escarpment is generally aligned north-northwest between Tukayyid and Abu Khanzir, though there are several swings from the general trend along its length. There are definite signs of faulting on the scarp, as at Khashm al Duda and Khashm al Dimand. At the south end of Khashm al Mahasa there are no obvious signs of faulting, but the "scarp face" is essentially the steepening south flank of an anticline. The feature is made up of folded very weathered Tuqayyid Limestone and overlying Zahra Beds. The area here looks slightly complicated, perhaps because of the cover of Zahra Beds. Minor anticlinal features can be observed west of the At Traq scarp, as at Kabd (Chabd), Uba'id, and Faydat Ar Radhuma.

Slightly northwest of the At Traq scarp is the Galaib scarp, where surface geology indicates a north-northwest faulting trend and general lineation in a similar direction, which is manifested also in the trend of the escarpment to the northwest of Galaib. This is considered to be a fault scarp having a possible throw of 100 feet in Ash Shawyyat area. Eighteen miles north of here, in the area of Shaikhya-Dhiriyat, is a series of parallel folds which show two axial trends introducing the additional north-south trend which may be related to the structural grain of the Salman area.

In the central part of the area between the Waqisah scarp in the west and At Traq belt in the east is a series of depressions which, considered as a group, show alignment in a north-northeast direction, convergent with the trend seen from Tukayyid through At Traq, Chabd, Galaib, and Ash Shawyyat. The As Salman depression forms one of the largest of this group. This is enclosed by high escarpments with repeated north-northeast trend surrounded by a horizontal plateau. About 100 kilometers northwest of the As Salman group of depressions is the Ash Shabakah (Shabicha) depression, which shows small anticlinal and synclinal folds in the Zahra Beds.

East of the At Traq group of scarps, Ghanimi anticlines, trending north-northwest and south-southwest, and Abu Ghar, a gentle north-south fold, are the dominant features. Between Abu Ghar and Al Basrah there is a slight topographic feature, which may be structural expression and which can be seen in the Shagra and Boliya areas.

Apart from the slight structural features of Ratawi, Rumaila, and Zubair there is no significant feature in the Al Basrah area except the dominating Jabal Sanam, which rises high above the surrounding flat country. Here, according to Boeckh and Viennot (1929), the old rocks project from below the Cenozoic cover. They stated that the rocks show a great resemblance to the Cambrian of the Persian Gulf.

The structural manifestations previously mentioned have been attributed to several different factors by various authors. Some stressed the role of diastrophism and epirogenic movements, and others emphasized the role of solution collapse. According to Dunnington (1958), "gravimetric data and slight structural manifestations in the flat-lying Tertiary cover provide evidence of important buried structural elements throughout the 'unfolded area.'" Lateral variations in sedimentary thicknesses over small distances are deductible, and it is concluded that most of these variations are controlled by pre-Miocene faulting of various dates, the relief due to faulting having been erased at the surface by subsequent erosion and deposition. The tectonic pattern suggested by the evidence is a complex one, resulting from interplay of vertical movements on fault trends which are oriented predominantly north to south, east to west, northwest to southeast, and northeast to southwest, the importance of individual trends showing marked local variations. Some of the prominent detected structural features are continuous for some tens or even hundreds of miles. Some pass beyond the limits of the region considered into Saudi Arabia. A few transgress directly across the limit of the unfolded area into the folded zone.

Where directional characters can be read into the complications, one or more of the four main tectonic trends discerned in the unfolded area is generally found to be involved. As a few important tectonic features on these trends pass directly from folded into unfolded terrain, it is argued that the folded zone was probably traversed prior to folding by a tectonic network comparable with the network that is now detectable in the unfolded area.

STRUCTURAL HISTORY

The Arabian shield dates from pre-Cambrian time. Since then, during various geological periods, the sea has transgressed and regressed over its margins. Western Iraq has undergone this sedimentary history as part of the fringing region (shelf) of this shield, the structural history of the area being reflected in the mode of sedimentation. From Triassic time this was controlled by the presence of the Ga'ara-Khaleisa feature in the north and the Arabian shield proper in the

southwest. The Triassic sediments indicate epicontinental conditions. The various unconformities in the geological sequence, considered with the nature of the sediments, point to several epirogenic movements which caused the advance and retreat of the sea over the area. Duration and extent of these movements are highly varied. The main ones occurred during late Bathonian and early Callovian times. The emergence was followed by a major transgression heralding the deposition of the Upper Jurassic Najmah limestones. A minor movement during late Berrisian and early Valanginian times has also been postulated to account for the deposition of the Yamama limestones on the Sulaiya Formation.

During the rest of Cretaceous time the area underwent a series of sedimentary cycles caused by marine transgressions and regressions. There are indications in the Cenomanian cycle that certain structural positive features, probably arcuate and extending from the Rumaila area, gave rise to the Mishrif reef. It was during the middle Turonian and lower Campanian cycle that the east-west-trending Anah graben trough formed. This trough continued subsiding during Maestrichtian time to accommodate the great thickness of sediments accumulated.

The Ga'ara high must have been near shore during the Cenomanian time, from the evidence of the Rutbah sandstones, and a slight transgression followed, culminating in the deposition of the Mishrif (or M'sad) Formation.

Late Cretaceous time was mainly a period of transgression, in which neritic limestones, including tongues of basinal sediments from the east side, were deposited.

The Eocene deposition was followed by a long period of emergence, which was ended by the deposition of the Euphrates limestones over most of the eastern parts of the area, while the western parts perhaps remained above sea level.

Further transgression during middle Miocene time led to the deposition of the clastics of the Ghar and lacustrine Zahra deposits and evaporites of the Lower Fars. During this period a more extensive area was covered, as evinced by the extensive Zahra beds.

During late Miocene and Pliocene times the Dibdiba clastics were deposited, the material derived possibly from a rapidly rising mass of the Arabian shield.

Since then, the central part of the area seems to have undergone relatively more uplift than the remainder, as can be seen in the distribution of the Zahra beds. Rejuvenation of the wadi system exposure area of Upper Cretaceous rocks may be considered as an indication of a sudden uplift and readjustment.

GRABEN SYSTEM

There is no direct indication of a graben system in the area; however, gravity-survey results, sedimentary history, and some seismic investigations demonstrate that even the flat-lying western desert area is underlain at depth (and locally at not very great depth) by buried structural elements and grabenlike faults of very considerable throw and shift. Some of these can be traced for very great distances into and across neighboring countries and some through a series of complex gravity features far into the zone of late Tertiary folding. The major tectonic elements of southwestern Iraq are shown in figure 1.

According to Dunnington (1960), the ages and trends of movement of these faults, and the nature of the faults themselves, remain for the most part obscure. Some, trending approximately east to west, may be identified with fair certainty as delimiting major troughs of subsidence which originated during Senonian time; thus, the east-west-trending Anah anticlinal structure has been formed on the site of a graben trough which dented and broke the Ga'ara-Khaleisa block during early Late Cretaceous time. Others, including some of north-south alignment, appear from subsurface evidence outside the area considered here, to have moved significantly in very Late Jurassic or very Early Cretaceous times, though they may have had a much older existence and may have been slightly dislocated in later times. There is the possibility of As Salman depressions being basically manifestations of a deep buried graben system, though greatly influenced and accentuated by subsequent solution collapse phenomena. A similar argument is also applicable to the other depression and solution features of the area. However, with the present degree of knowledge and the inadequacy of available data, it would be dangerous to give rein to speculation and imagination.

SUMMARY

The study region comprises more than 82,000 square kilometers of southwestern Iraq and lies in the northeast side of the Arabian Peninsula. We owe much if not all our knowledge of the geology of this area to the exploration for oil, over almost a quarter of a century, by the Iraq Petroleum Company and its associate, the Basrah Petroleum Company.

In western Iraq near the Ga'ara area the oldest rocks are considered to belong to the Lower Triassic (?). They are succeeded by the Rhaetic, Liassic, and Bajocian-Bathonian sequence. In the same area a major erosional gap exists between the Middle Jurassic and the middle Cretaceous. This gap narrows away from the Ga'ara massif. Thus, it is possible to recognize suc-

cessive occurrences of the intervening formations basinward.

The Cretaceous System shows strong diachronism and a history of sedimentation characterized by sedimentary cycles, which were controlled by the epirogenic withdrawals over the Arabian platform. The basic near-shore to basin sequences are hardly recognizable there, the sediments having been laid down close to the old shorelines. The main Cretaceous cycles are: Tithonian (Upper Jurassic) to Aptian, Aptian, Cenomanian to lower Turonian, Middle Turonian to lower Campanian, and upper Campanian to Maestrichtian.

Similar cycles are detectable in the Tertiary, but their significance can only be appreciated if other areas of Iraq are considered. In particular, the understanding of Miocene stratigraphy is in a state of flux and requires a great deal of investigation. The Oligocene Series is not recognized in the area.

Structurally, the area lies in the Interior Homocline of the Arabian Peninsula. It is flat-lying country with gentle dips to the east and northeast. Minor northwest- and north-trending linear structural features occur in the Tertiary outcrop area. These may be due to recurrent disturbance along old lines of weakness, accompanied by the dissolution of the evaporites in the Paleocene and Eocene sequence. Solution-collapse structure is well developed in many places.

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GEOLOGY OF THE ARABIAN PENINSULA

Eastern Aden
Protectorate and
Part of Dhufar



Geology of the Arabian Peninsula

Eastern Aden

Protectorate and

Part of Dhufar

By Z. R. BEYDOUN

GEOLOGICAL SURVEY PROFESSIONAL PAPER 560-H

A review of the geology of the Eastern Aden Protectorate and part of Dhufar as shown on USGS Miscellaneous Geologic Investigations Map I-270A, "Geologic Map of the Arabian Peninsula," 1963



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FOREWORD

This volume, "*The Geology of the Arabian Peninsula*," is a logical consequence of the geographic and geologic mapping project of the Arabian Peninsula, a cooperative venture between the Kingdom of Saudi Arabia and the Government of the United States. The Arabian-American Oil Co. and the U.S. Geological Survey did the fieldwork within the Kingdom of Saudi Arabia, and, with the approval of the governments of neighboring countries, a number of other oil companies contributed additional mapping to complete the coverage of the whole of the Arabian Peninsula. So far as we are aware, this is a unique experiment in geological cooperation among several governments, petroleum companies, and individuals.

The plan for a cooperative mapping project was originally conceived in July 1953 by the late William E. Wrather, then Director of the U.S. Geological Survey, the late James Terry Duce, then Vice President of Aramco, and the late E. L. deGolyer. George Wadsworth, then U.S. Ambassador to Saudi Arabia, and Sheikh Abdullah Sulaiman, then Minister of Finance of the Government of Saudi Arabia, lent their support to the plan. In November of the following year, 1954, Director Wrather approved the U.S. Geological Survey's participation and designated G. F. Brown responsible for the western Arabian shield region in which he had previously worked under U.S. foreign-aid programs. In January 1955 F. A. Davies, Chairman, Board of Directors, Arabian-American Oil Co., approved Aramco's participation and appointed the late R. A. Bramkamp, chief geologist, responsible for compilation of the area within the Kingdom where the sediments crop out. This responsibility fell to L. F. Ramirez following the death of R. A. Bramkamp in September 1958.

R. A. Bramkamp and G. F. Brown met in New York in February 1955 and planned the program, including scales of maps, areas of responsibility, types of terrain representation, and bilingual names. Thus there was established a cooperative agreement between the Kingdom of Saudi Arabia, the U.S. Department of State, and the Arabian-American Oil Co. to make available the basic areal geology as mapped by Aramco and the U.S. Geological Survey.

The agreement specified publication of a series of 21 maps on a scale of 1:500,000, each map covering an area 3° of longitude and 4° of latitude. Separate geologic and geographic versions were to be printed for each of the quadrangles; both versions were to be bilingual—in Arabic and English. A peninsular geologic map on a scale of 1:2,000,000 was to conclude the project.

High-altitude photography, on a scale of 1:60,000, of the Kingdom of Saudi Arabia was initiated during 1949 by the Aero Service Corp. and completed in 1959. Both third-order vertical and horizontal control and shoran were utilized in compiling the photography. This controlled photography resulted in highly accurate geographic maps at the publication scale which then served as a base for the geologic overlay. The topography of the sedimentary areas was depicted by hachuring and that of the shield region by shaded relief utilizing the airbrush technique.

The first geographic quadrangle was published in July 1956 and the last in September 1962. While preparation of the geographic sheets was in progress, a need arose for early publication of a 1:2,000,000-scale peninsular geographic map. Consequently, a preliminary edition was compiled and published in both English and Arabic in 1958. The second edition, containing additional photography and considerable new topographic and cultural data, was published in 1963. The first of the geologic map series was published in July 1956 and the final sheet in early 1964. The cooperative map project was completed in October 1963 with

the publication of the 1:2,000,000-scale "Geologic Map of the Arabian Peninsula" (Miscellaneous Geologic Investigations Map I-270 A).

As work on the quadrangles progressed, geologists, companies, and governments working in areas adjacent to the Kingdom of Saudi Arabia were consulted by Arameo and invited to participate in the mapping project. The number of cooperating participants was expanded to 11, which included the operating oil companies in the peninsula and which are identified elsewhere in this text; the Overseas Geological Surveys, London; the Government of Jordan; F. Geukens, who had worked in Yemen; and Z. R. Beydoun, who had studied the Eastern Adu Protectorate. With the close cooperation of the authors, the new data were added to data already plotted on the base map of the Arabian Peninsula.

As the geological coverage of the peninsular map grew, the need for a text to accompany the map became apparent to both the U.S. Geological Survey and the Arameo geologists. Exploratory conversations were begun by Arameo with companies working in the other countries of the Arabian Peninsula for their participation in the preparation of a monograph on the geology of the Arabian Peninsula. Each author prepared a description of the geology of the area for which he was responsible, as shown in the sources of geologic compilation diagram on the peninsular map. The U.S. Geological Survey undertook the publishing of the volume as a professional paper, and the Government of Saudi Arabia was to finance its printing. It was early agreed that there would be no effort to confine the contributions to a standard format and that no attempt would be made to work out an overall correlation chart other than shown on the "Geologic Map of the Arabian Peninsula." Thus, the individual style of authors of several nationalities is preserved.

Cooperation and relations have been of the highest order in all phases of the work. The project would not have been possible without the full support of the U.S. Department of State, the Kingdom of Saudi Arabia, and all contributors. In fact, the funds which made publication of this volume possible were contributed the Saudi Arabian Government.

The data provided by the maps and in the professional paper provide information for an orderly scientific and economic development of a subcontinent.



O. A. SEAGER,
Arabian-American Oil Co. (Retired).



W. D. JOHNSTON, JR.,
*Former Chief, Foreign Geology Branch,
U.S. Geological Survey.*

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 3. Columnar sections of the Cretaceous of the Eastern Aden Protectorate.
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 5. Schematic regional correlation of stratigraphic units in south Arabia and former British Somaliland.
 6. Selected structural cross sections, Eastern Aden Protectorate.

FIGURE 1. Tentative correlation of Lower Cambrian(?) sedimentary rocks, from south Oman ('Uman) to southwest Hadramawt (E.A.P.)..... H10

GEOLOGY OF THE ARABIAN PENINSULA

EASTERN ADEN PROTECTORATE AND PART OF DHUFAR

By Z. R. BETDOON¹

ABSTRACT

This account is divided into four parts. The first outlines the position of the Eastern Aden Protectorate and part of Dhufar and (a) includes an account of previous geological work carried out, (b) outlines the fieldwork since 1953 done for the Iraq Petroleum Company, Ltd., and associated companies under the leadership of the author, the results of which form the body of this account, and (c) incorporates earlier results with acknowledgment of the very substantial contribution of colleagues and specialists.

The second part discusses geography of the area and accessibility and operating conditions.

The third part describes and discusses the stratigraphy. Basement, Jurassic, Cretaceous, and Tertiary sedimentary rocks are divided into lithostratigraphic units for which description, faunal lists where applicable, regional correlation of formations with neighboring countries, and economic aspects of various formations are given. Sedimentary and intrusive-extrusive Precambrian and lower Paleozoic(?) (basement) rocks are classified and described, and a probable reconstruction of basement events from field and laboratory observations is given. The basement rocks were in part subjected to low-grade metamorphism, folded, faulted, cleaved, and maturely eroded. Intrusive activity may have extended into the Upper Silurian, as suggested by some isotope age determinations. The oldest rocks overlying the basement peneplain are Middle and Upper Jurassic(?); these consist of basal sands, limestones, marls, and local evaporites. The Cretaceous transgression advanced from the east, and the oldest datable sedimentary rocks are Barremian. Lower to Upper Cretaceous sediments were laid down over the entire area, being predominantly clastics in the west and carbonates in the east, but intertonguing. The Tertiary Period began with a widespread Paleocene transgression during which cliff-forming limestones were deposited over the whole area; these were followed by lower and middle Eocene shales, limestones, and evaporites, and then by regional uplift and gentle folding and faulting. Oligocene and Miocene clastics, reef limestones and local evaporites were then deposited in coastal embayments.

The fourth part discusses structure, including (a) a general introduction, (b) description of structural development of the area in the Tertiary, as those events were responsible for the present broad structure of the territory, (c) an interpretation of the Tertiary structure in the area and across the Gulf of Aden in former British Somaliland, (d) examination of evidence from the Somali side with discussion of earlier views, and (e) a brief

outline of structural history of the Eastern Aden Protectorate and Dhufar.

In the interpretation of the Tertiary structure, the development of the biaxial Hadramawt arch (Hadhramut arch) and a comparable Somali arch are attributed to regional compression which buckled the whole thickness of the crust. Important block and step faulting which followed buckling collapsed the flanks of the arches facing the Gulf of Aden.

INTRODUCTION

LOCATION

The area treated here is the Eastern Aden Protectorate (E.A.P.) which comprises the Provinces of Hadramawt (Hadhramut²) in the west and Al Mahrah (Mahra) in the east. Also partly treated is the Province of Dhufar of the Sultanate of Muscat and Oman adjoining the E.A.P. on the east.

The E.A.P. occupies the eastern part of the strip of territory on the southern and southwestern part of the Arabian Peninsula known as the Aden Protectorate, which stretches from Bab al Mandab straits at the southern end of the Red Sea, east-northeast along the southern edge of the Arabian Peninsula to the borders of Dhufar. The western part of the Aden Protectorate is known as the Western Aden Protectorate (W.A.P.).

The northern border with Saudi Arabia is largely undemarcated, but the presently operative boundary takes in the southern fringes of the sands of the Rub' al Khali (Empty Quarter), giving the E.A.P. some 90,000 square miles of area.³ The area of Dhufar is about a third of that of the E.A.P.

The Hadramawt Province consists of the Qu'ayti State of Ash Shihr (Qu'ayti State of Shihr) and Al

¹ Of the Iraq Petroleum Company, Ltd.

² Different spellings of place names which occur in parentheses are those preferred by the author and differ from spellings on the map. Generally they are given only the first time the word appears in the text.

³ This includes the Wabdi State which, however, joined the South Arabian Federation in 1962 and is no longer an administrative part of the E.A.P. In early 1943 this federation became the Federation of Aden and Southern Arabia. See plates 3 and 4 for E.A.P. operative borders.

Mukallā (Mukalla), which is the largest and richest state and has its capital at Al Mukallā; the Kathiri State of Say'un (Sayun), which is a much smaller state forming a wedge within the Qu'ayfi State, has no access to the sea, and has its capital at Say'un in Wādī Ḥaḍramawt; and, for the purpose of this account, the Wāhidi State, which occupies the southwest corner of the E.A.P. and has its capital at Mayfa'ah.

The Al Mahrah Province occupies the eastern half of the E.A.P. and forms the mainland part of the Mahri State of Qishn and Socotra. Except for its northern part, the territory is largely administered and nominally ruled by the Sultan resident in Ḥadibū, on Socotra Island. Dhufar is administered by a Wali in Salālah for the Sultan, though of late the latter has been in residence at Salālah.

PREVIOUS INVESTIGATIONS AND PRESENT WORK

Reports by various travelers in the second half of the 19th and the early part of the 20th centuries contributed something to the geological knowledge of the E.A.P. The first geological account for any part of the territory was by Carter (1852), who gave a good description of coastal geology and sections along the whole south Arabian coast as observed from the sea and from selected brief landings. Manuscripts of the 1898-99 Austrian expedition to south Arabia (for example, Kossmat, 1907) include observations on coastal geology at Ballāf-Bi'r 'Alī, Wādī Mayfa'ah, Al Mukallā, the Mahrah coast, and Ra's Fartak (Fartaq); these manuscripts were used by Wissmann (Wissmann and others, 1942). Thompson and Ball (1918) spent a short time in the Al Mukallā area studying lignite prospects. Little (1925) spent about 6 months in 1919-20 making a geological investigation of the Al Mukallā region as far west as Wādī Ḥajr (Hajar); his report is the first systematic stratigraphic and paleontological account of Ḥaḍramawt. Lees (1928) gave a more recent account of Dhufar geology since Carter (1852), in his paper on Oman and southeast Arabia.

In 1931 and 1939 Hermann von Wissmann and van der Meulen took part in two expeditions in the E.A.P. The first crossed up into the Wādī Ḥaḍramawt basin from Al Mukallā, returning by the Wādī Ḥajr basin. The second was an overland crossing through the W.A.P. to the 'Iyādh ('Ayad) salt dome and across to the Wādī Ḥaḍramawt basin via the western part of the Southern Plateau. From Wādī Ḥaḍramawt the first penetration northward over part of the Northern Plateau was made as far as Tanis; from there, the expedition turned back to Wādī Ḥaḍramawt and the coast. Traverse mapping along routes followed, and tectonic and some stratigraphic investigation based on

Little's stratigraphic conclusions were carried out (Wissman, 1932; Wissman and others, 1942).

In 1937-38 Miss Freya Stark led an expedition including Miss E. A. Gardner, geologist, and Miss G. W. Caton-Thompson, archeologist, which carried out work in the Wādī 'Amd and Wādī Daw'an areas of Ḥaḍramawt and visited other parts; the geological studies were mainly concerned with Pleistocene to Recent deposits (Caton-Thompson, 1938; Caton-Thompson and Gardner, 1939).

Simultaneously with the Stark expedition, R. W. Pike and H. R. Wofford were carrying out the first general geological reconnaissance of the territory for the Iraq Petroleum Company, Ltd. (I.P.C.). This was a combined air and ground expedition of about 6 months duration. Some structural mapping was done in Wādī Ḥaḍramawt, on a part of the Southern Plateau, and in the area between Ash Shihr and Al Mukallā; some stratigraphic work, based on Little's stratigraphic divisions, was done in these areas and in the Nā'ifah (Nayfa) area of Wādī Ḥajr.

R. W. Wetzel and D. M. Morton in 1947-48 made the first detailed stratigraphic study in the E.A.P. for I.P.C. Their expedition concentrated mainly on the southern part of the Al Mahrah Province of the E.A.P. from Muṣayni'ah (Musayna'ah) to Damqawt near the Dhufar border, and in the Wādī al Jiz' (Jesa') and Al Masilah (Wādī al Masilah) basins. Some work was done in the vicinity of Al Mukallā and in Wādī Ḥaḍramawt and along the two routes between them. The area west of Al Mukallā was not visited, but Dhufar was examined. This expedition stayed some 4 months in E.A.P. and 2 months in Dhufar; it established the basis of currently used E.A.P. stratigraphy, completely revising Little's (1925) Tertiary divisions and adding considerably to the Cretaceous stratigraphy. C. S. Fox spent a few weeks in 1947 on a geological reconnaissance of Dhufar for the Government.

Another expedition by Wetzel and Morton in 1949 visited Ḥaḍramawt, concentrating on the salt-dome areas of Shabwah and 'Iyādh in the western part of Ḥaḍramawt, and on the adjoining Bayhān area of the W.A.P. Some further work was done in the vicinity of Al Mukallā. The expedition was of some 2 months duration.

Beginning late 1953, various expeditions for the I.P.C. led by the author worked for six consecutive field seasons in the E.A.P., carrying out geological mapping and stratigraphic and structural investigation throughout most of the territory. Similar but more limited fieldwork (unpub.) was done in Dhufar by Dhofar Cities Service geologists after 1953.

During the course of the recent E.A.P. work, reconnaissance topographic mapping was done to supplement the limited reliable maps available (Bunker, 1953; Thesiger, 1947, 1948, 1949; Wissmann, 1959) and to serve as base for the geological map. Reconnaissance geological mapping of the northern part of the E.A.P. was based on traverses tied to astronomical fixes, supplemented by measuring stratigraphic and structural sections and by sampling at various localities. Some detailed geological mapping with plane table and telescopic alidade was also done. However, since much of the E.A.P. is covered by very gently dipping Tertiary sedimentary strata, with older rocks exposed only in deeply cut gorges, in the much faulted southern part, and in the western borders, the work became a stratigraphic investigation and a study of tectonic behavior. Emphasis was on facies and thickness changes in Mesozoic sedimentary rocks, but with considerable work on older and younger rocks. For this the coastal areas were ideal. The southwestern and southeastern parts of the territory were also mapped from aerial photographs, and geological interpretation was done by the author.

A great number of stratigraphic sections were sampled and measured, and a considerable number of field samples were collected both for paleontological study and for field correlation and microfacies comparison; the majority of these samples have been sectioned and have been examined by specialists.

The present work is the result of all the above geological investigations carried out in the E.A.P. between 1953 and 1959 by the author with the collaboration, assistance, and specialist work of colleagues in and outside the I.P.C. Revisions of conclusions in those reports have been made by the author in the light of new field evidence as it became available.

Group, formation, and member divisions of lithostratigraphic units have been described by the author, revising nomenclature by Wetzel and Morton and incorporating new names from the recent work; the results are given in the text and illustrations of this paper.

Geophysical work in the northern part of the E.A.P. by the I.P.C. was done from late 1955 until early 1960. This work consisted of a gravity survey for four field seasons terminating in 1959, an airborne magnetometer survey in 1956, and a short season of seismic survey terminating in April 1960.

Some shallow-hole water-well drilling was also carried out between 1956 and 1959; the deepest well drilled was 602 feet. Information from the eight boreholes drilled did not contribute much more to the stratigraphy than was already known from surface investigations.

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GEOGRAPHY

MOUNTAINS, PLATEAUS, AND PLAINS

A discontinuous coastal plain of variable width is bordered by the coastal mountain belt. The plain is composed largely of gravel flats and alluvium interrupted by cliffs of older rock and some tracts of Recent lavas and Pliocene and Recent raised beaches, terraces, and dune areas. The coastal mountain belt is the block-faulted southern flank of the Hadramawt structural arch, the faults giving rise to a mountainous region of rugged relief. The mountain belt is wide in the west but is narrower and somewhat diminished in

height eastward. In the western part where the basement is exposed, the country is rough and broken by a complicated system of faults involving basement, Mesozoic, and Tertiary rocks. Elevations reach nearly 2,000 meters above sea level in places. To the east in Al Mahrah the Tertiary and Cretaceous beds are involved in a marked development of fault scarps, giving the area steep but more regular relief.

Forming the relatively unfaulted northward continuation of the coastal mountains is the Southern Plateau or Jawl; it forms the axial area and flank of the structural South Hadramawt arch. Its northern boundary is in the Wādī Hadramawt-Al Masilah and the Wādī al Jiz' (Wādī Jeza') structural depressions. The structural trend of this plateau is a very gentle tilt northward and eastward. The plateau is a tableland of Paleocene limestone capped by mesas and cuestas of Eocene age, and it is cut by an intricate network of drainage which has excavated deep gorges to expose underlying Cretaceous sedimentary rocks in many places. Its western end is abruptly truncated in an escarpment bordered by the plain of Jaww Kudayf (Khudayf). In the east, the north-south coastline from Ra's Fartak truncates it, and it is bordered by Al Qamar Bay. Al Masilah cuts across its eastern part obliquely, across the plunge of the axis of the South Hadramawt arch.

Separated from the Southern Plateau by the Hadramawt-Al Jiz' synclinal basin is the Northern Plateau or Jawl. It follows the pattern and description of the Southern Plateau, being virtually its northward extension; the Northern Plateau slopes from an axial region southward toward the Wādī Hadramawt-Al Jiz' syncline and very gently northward to the Rub' al Khālī desert. This plateau is the physiographic representation of the structural North Hadramawt arch. Like the Southern Plateau, the Northern Plateau is also gently tilted eastward, being highest in the west (calculated 1,200 m), where it also is abruptly truncated by an escarpment line trending northeast, which separates it from the Western Plains; this escarpment is probably fault controlled at depth. Eastward the plateau merges into the Al Qarā' Mountains and Najd of Dhufar. The plateau is also a Paleocene tableland capped by mesas and cuestas of Eocene, but here younger Eocene sedimentary strata are preserved over a much wider area. In the west in deep gorges and along the escarpment line, Cretaceous sedimentary rocks are exposed. Faulting is hardly apparent on the surface. The southern side of the Northern Plateau in Dhufar is formed by the coastal mountain escarpment which is in part faulted.

Bordering the western edges of the Southern and Northern Plateaus are two tracts of plain. The Jaww al Kudayf Plain extends from the western end of the Southern Plateau escarpment westward to the edge of the basement area of the W.A.P. It is an area of light gravel and sand ranging from some 950 to 800 m above sea level and includes within it the hills of the Shabwah and 'Iyādh areas—salt domes and Cretaceous outliers. Drainage from the Southern Plateau and from the Al Kawr ranges of W.A.P. enters this plain and flows northward toward the Ramlat as Sab' atayn sand-dune region which forms its northern boundary. Near the Southern Plateau, extensive gravel and scree terraces can be seen. Faulting, which has affected the Southern Plateau, has been responsible for uplifting the salt domes of the area.

The Western Plains adjoins the western extremity of the Northern Plateau and is bordered respectively on the north and south by the sand dunes of the Rub' al Khālī and Ramlat as Sab' atayn sand deserts; the area is some 900 m (in the west) to 650 m (in the northeast) above sea level and stretches into Yemen and Saudi Arabia. Scattered low hills and mesas of Cretaceous rocks occur, some with a capping of Paleocene limestone; the main belt of these hills stretches from the Al 'Abr area northward to the Ash Sharawah scarp and breaks up the Western Plains into two flat areas of gravel and sand. In the western part, basement igneous and metamorphic rocks are preserved above the surrounding gravels and blown sand of the plain.

Stretching between the Rub' al Khālī sand desert in the north and the dissected gently dipping north flank of the Northern Plateau is an area of flat gravel plain, in places broken by low eroded ridges and scree hills of Eocene age and by migratory small sand dunes; this area can be termed the "Northern Plains." It is in fact a continuation of the flank of the North Hadramawt arch. In the west the area begins approximately at long. 49° E. where it is narrow, but it becomes progressively wider eastward until it is about 60–80 kilometers wide near the Dhufar border. The plain continues eastward across the Dhufar to south Oman, to merge into Jiddat al Harāsis. Drainage from the Northern Plateau of the E.A.P. and Dhufar cuts it in very broad, shallow wīdyan (dry water courses). Elevations are between 550 m above sea level in the west and about 250 m in the east.

SAND-DUNE AREAS

The Rub' al Khālī sand desert (the Empty Quarter) is a huge area of sands, only the southern fringes of which fall in the E.A.P. and Dhufar. Here the dunes are mainly distributed in parallel to subparallel ridges

called locally 'urūq, separated by narrow, flat stretches of gravel, gypsum, or silt, referred to locally as shuqūq. The trend of the southern border of the Rub' al Khālī is east-northeast, which also is roughly the trend of the dune ridges, some of which are as much as 150 m high. Areas of confused dunes, "block" dunes, and dune massifs occur at various localities along the southern fringes, particularly at the mouth of Wādī Makhyah (Wādī Ḥazar, long. 49° E.) where periodic floods and possibly funneling of winds may be responsible.

Slip faces of dunes are generally south (Bunker, 1953), but some northward slip faces have been observed. Crescent dunes as outliers are common (for example, at the mouth of Wādī Khudrah). Although some migration of dunes takes place, for the main dune ridges the migration seems to be offset by seasonal changes in wind directions, so that migration in any specific direction is difficult to detect. Brown (1960) mentioned south and southeast to east as the dominant directions of sand movement indicated for the southwest part of the Rub' al Khālī. Bagnold (1951) mentioned that the wind blows from both northerly and southerly quadrants, winds from the easterly and westerly quadrants being infrequent. This would account for counterbalancing of sand migration to some extent, though the effect of thermal disturbances and the inland effect of the southeast (winter) and southwest (summer) monsoons must also be contributing factors. As yet no consistent records have been kept and any conclusions remain speculative, being based on observations made in the field at irregular intervals.

A much smaller sand area than Rub' al Khālī and isolated from it is Ramlat as Sab'atayn sand desert. It stretches eastward from the foothills of Yemen and Bayḥān where it is some 100 km in width, into the Wādī Ḥaḍramawt basin, roughly occupying the western extension of the Wādī Ḥaḍramawt structural trough. The dunes lose both height and lateral extent eastward until they die out as low isolated patches of sand some 5 km in width near Shibān in Wādī Ḥaḍramawt. The Ramlat as Sab'atayn area is again one of dune ridges which, however, are less regular than those of the Rub' al Khālī; they roughly trend east-northeast in the west, are some 50 m in height, and arch and become irregular in the east. Various hill outcrops of Cretaceous and metamorphic rocks rise above the dunes in some parts, and in Yemen and Bayḥān two salt domes occur within the sand area. As in the Rub' al Khālī, the shuqūq often show silt surfaces, remnants of ancient drainage; in some parts pumice bombs have been found on the surface, though no volcanoes are known from anywhere in the vicinity. These have probably been transported by flood water from the vicinity of Ma'rib in Yemen.

Migration of sand is largely offset by seasonal changes in the prevailing winds and by thermal disturbances (see previous discussion).

There are only two other noteworthy sand-dune areas in the E.A.P., the bigger in the Wādī Mayfa'ah basin in the Wāḥidī State and the smaller in the vicinity of Qishn in south Al Mahrah.

DRAINAGE

With two exceptions the drainage system of the E.A.P. consists of dry water courses or widyān, which only flow in times of heavy rains in flash floods. Some are very deeply cut, with sides more than 300 m in elevation above the water course; others are wider with less steep sides; and others are broad and flat. Wādī Ḥajr is perennial from its headwaters to the sea, and parts of Al Masilah are perennial though not, however, reaching the sea. The coastal widyān of Dhufar are short and a number have water until they enter the salālāh plain.

The drainage system can be divided into coastal widyān, the Wādī Ḥaḍramawt-Al Masilah and Wādī al Jiz' systems, and widyān flowing to the Rub' al Khālī.

Coastal widyān, with some exceptions, flow in a general southeast direction turning more southerly near the coast; most of these widyān are less than 100 km in length. They head in the coastal mountain belt or the Southern Plateau and cut back to the watershed. The majority of the widyān are torrential and have steep gradients; in the main they are not easily traveled by motor transport.

The widyān flowing to the Rub' al Khālī sand desert are on the whole long and shallow and trend in a north-northeast direction, though Wādī 'Atinah in Dhufar runs east-northeast parallel to the edge of the Rub' al Khālī. They head in the vicinity of the axis of the North Ḥaḍramawt arch, which also forms the highest part of the Northern Plateau and of the Al Qari' Mountains of Dhufar. In the west they cut through Paleocene limestone to Cretaceous sandstone in places, but eastward they expose only Eocene beds. Most of them cut across the Northern Plains, but some lose identity before reaching the Rub' al Khālī.

The Wādī Ḥaḍramawt-Al Masilah and Wādī al Jiz' systems collect drainage from the greater part of the plateaus. They roughly occupy (except for the lower part of Al Masilah) the structural synclinal depression between the North and South Ḥaḍramawt arches. Wādī Ḥaḍramawt in its western end is really a wide basin some 50 km in width, forming part of the Western Plains and the Jaww al Kudayf Plain, with the dune area of the Ramlat as Sab'atayn in between. The Wādī narrows rapidly eastward until it is only some 2-3 km wide below Tarim, its canyon walls being

the escarpments of the Northern and Southern Plateaus. The tributaries debouching into Wādī Ḥaḍramawt-Al Masilah are generally long and very deeply cut gorges that are gentle in gradient, commonly filled with loess or alluvium, and generally accessible. These gorges, like Wādī Ḥaḍramawt-Al Masilah, have cut through the Paleocene limestone tableland to expose in places the Cretaceous below, and the cliffs forming the sides are about 300 m or more in height, becoming lower eastward. The southern tributaries are longer than the northern ones. The tributaries rise near the axes of the South and North Ḥaḍramawt arches, collect in the Wādī Ḥaḍramawt synclinal area, flow easterly, and, as Al Masilah, obliquely cut across the eastern plunge of the South Ḥaḍramawt arch to reach the sea in south Al Mahrah.

Widyan flowing northward in the Jawwal Kudayf plain and southward in the Western Plains die out in the Ramlat as Sab'atayn sand desert, but underground their floodwater joins the Ḥaḍramawt-Al Masilah system.

The gentle syncline of Wādī Ḥaḍramawt continues eastward across low-relief country to take in the Wādī al Jiz' system. This forms the gathering drainage for widyan from the eastern parts of the Northern and Southern plateaus and flows eastward to the sea in Al Qamar Bay. The Al Jiz' basin is one of more gentle relief than that of Wādī Ḥaḍramawt, and the tributary widyan are less deeply incised.

Wissmann, Rathjens, and Kossmat (1942) and Bunker (1953) have discussed the physiography and morphology of the Wādī Ḥaḍramawt system in some detail.

MORPHOLOGY AND STRUCTURE

The structural sequence of events is briefly outlined here but is dealt with in more detail on page H41. General uplift of the E.A.P. and Dhufar, with resultant upwarping and faulting, occurred in the terminal Eocene. The North and South Ḥaḍramawt arches and the synclinal downwarp of the Ḥaḍramawt-Al Jiz' region were elevated at that time; further movement occurred in the late Miocene and more faulting occurred in the Pliocene. The present-day drainage system was thus initiated with the main terminal Eocene uplift and established in the late Miocene (early Neogene). Wissmann, Rathjens, and Kossmat (1942) believed that uplift in Yemen occurred earlier, the Paleocene shoreline lying somewhere in the W.A.P. and Yemen. Progressive arching in the E.A.P. and Dhufar continued in the Eocene until final emergence, the sea retreating, probably slowly eastward at first and then more rapidly, although oscillations in structural development likely occurred.

Structural embayments in the Oligocene and Miocene enabled sea water to encroach a little onto the landmass, but further movement in the late Miocene (early Neogene) with accompanying step and block faulting gave the final touches to an established morphology and drainage system. Oscillations in the Pliocene and later have caused rejuvenations of drainage and further cutting of the widyan that are tributary to Wādī Ḥaḍramawt. Some southward shift of the axis of the North Ḥaḍramawt arch, as previously postulated (Wissmann and others, 1942) for the Ḥaḍramawt syncline, may have occurred and would account for the deep cutting of the heads of the northern tributaries to Wādī Ḥaḍramawt.

Thus, the terminal Eocene and Miocene (early Neogene) structural movements initiated and then established and controlled the morphology and physiography of the region. Pedimentation in the extreme western part due to slow uplift in the Paleocene commenced to lay bare the Western Plains and expose the basement of the Ar Rayyān-Ath Thaniyah-Bayhān areas. Uplift together with cuesta formation, in the west of the E.A.P. probably started at the end of the middle Eocene.

CLIMATE AND VEGETATION

The E.A.P. is affected by the monsoon winds of the Indian Ocean region, but these, because of regional physical considerations, do not bring regular rainfall to the territory. The Salālah area of Dhufar is, however, blessed with regular summer monsoon rain.

The monsoons blow in two seasons. The winter monsoon from October to April blows from the southeast or east-southeast; winds are moderate and, although rough seas are frequent, there are often periods of calm. Clouds are frequent, but rain is sporadic and often occurs only as localized showers. The end of the winter monsoon may, however, bring heavy rain over a great part of the area, but such heavy rain is the exception rather than the rule. The summer monsoon from June to August blows from the southwest; winds are violent, the seas are very rough, and gusts may reach 100 km an hour. Only sporadic rain falls in the E.A.P. Though the chances of widespread rain are greater during the summer monsoon than during the winter monsoon, 2 or 3 years may pass between worthwhile falls. No reliable records of rainfall are available but along the coast the average annual rainfall is probably 3-4 inches, much of which may fall in one storm. In coastal Dhufar, because of regular rainfall, the coastal slopes are lush with vegetation and streams and pools abound. The streams mainly flow underground on entering the plain.

In the interior of the plateaus, diurnal range in temperature is as much as 50°F. Frost is common in January and February, whereas day temperatures can rise to 90°F or more. In the summer the night temperatures are much higher and the day maximum can reach 130°F. Along the coast the diurnal range is less, winter minimum being around 50°F and maximum being about 85°F. In the summer the maximum is higher, but the humidity is often less when the violent monsoon is blowing. The months of May and September are those between the monsoons and are of very high humidity and heat and little or no breeze.

At various times in the interior, cold dust-laden winds coming from the heart of Arabia blow from the north for a few days at a time in the winter, and similar hot sand-laden winds blow in the summer. The effects of the monsoons are less regular in the extreme north. Dusty conditions are general in the summer and visibility between June and September is generally poor or very poor.

The vegetation of the E.A.P. is on the whole sparse, the plateaus being mainly barren except in wādi beds where a flora of bunch grass, camel thorn, acacia, tamarisk, and ilb grows. In the main wīdīyān and parts of the coast where water is available for irrigation or where floodwaters are used, date palms, millet and other grain, some cotton, vegetables, and tobacco are grown, and thick concentrations of deciduous trees occur in places. Coastal Dhufar being more blessed by regular rain has a much more lush natural vegetation which is, however, basically similar to that of the E.A.P. Dhufar is the ancient home of the frankincense tree.

ACCESSIBILITY AND OPERATING CONDITIONS

Ḥaḍramawt and northern Al Mahrah possess a number of important dirt motor tracks which link the coast to the interior, to W.A.P., and to Aden. South Al Mahrah possesses no motor tracks. In Dhufar tracks link the Salālāh area with the north and with Ra's Naws (Ras Nus) in the east.

Al Mukallā is the main port for Ḥaḍramawt and supplies the Qu'ayṭī and Kathīrī States. It has limited dock facilities for coastal steamers and sailing dhows, but some large cargo-passenger ships make regular calls there.

Generally, the greater part of the E.A.P. is accessible to Land Rovers or an equivalent type of vehicle. Most wīdīyān can be used over at least parts of their lengths, some with comparative ease, and some with difficulty requiring improvised road building or track clearing. The Northern Plateau is navigable over all its extent in this way, though the extreme west is not easy. The same remarks apply to Dhufar.

West of long. 49°30' E., the Southern Plateau, is largely accessible to vehicles of the Land Rover type, but much of the way is very winding owing to the dendritic pattern of deeply cut wīdīyān. Eastward the area is largely inaccessible.

The E.A.P. is linked to Aden by regular air services calling at Al Mukallā and points in Wāḍī Ḥaḍramawt and Mayfa'ah. Dhufar has no regular air services, but a landing ground and station at Salālāh handle oil-company aircraft and an occasional commercial flight.

Wireless stations at Al Mukallā and Say'ūn link the E.A.P. via Aden with any part of the world.

STRATIGRAPHY

GENERAL

TIME UNITS REPRESENTED

Time units represented in the E.A.P. (and Dhufar) include rocks of Precambrian age and some sedimentary rocks of probable early Paleozoic age; intrusive rocks of early Paleozoic age are found in several localities. A long time gap exists between these early rocks which are grouped together under the term "basement," and the next time units present; these are Mesozoic sedimentary rocks of the Jurassic Period overlain by strata of the Cretaceous Period. The Cenozoic Era is represented by widespread Paleocene and Eocene sedimentary rocks.

GENERAL DISTRIBUTION OF SYSTEMS AND DOMINANT ROCK TYPES

The basement rocks crop out in the southwest part of the area from Al Mukallā westward into W.A.P. and in the Jabalath Thaniyāh area of the Western Plains. These rocks range from metamorphic gneisses and schists and rocks affected by granite invasion in the western part to less highly metamorphosed and unmetamorphosed sedimentary rocks in the eastern part; in this eastern area are large expanses of extrusive rocks. Intrusive bodies ranging from intermediate to silicic occur in various parts of the basement area. Farther east in Al Mahrah, a limited exposure of the Precambrian and Paleozoic igneous rocks and some Precambrian(?) and early Paleozoic(?) metasedimentary rocks occur at Ra's Sharwayn. No further exposures are seen till the coastal part of Dhufar is reached. There, in limited outcrops near Al Ḥawṭah (El Hota)—[west of Ra's Sājir (Sajar) and 'Ayn Sārīt]—are a series of graywackes, sandstones, shales, and mudstones of probable early Paleozoic age. A little to the east, from Mīrbāt (Murbat) to Ra's Naws and in the Kuria Muria Islands offshore, and older basement of Precambrian gneisses, schists, intrusives, and dikes and sills is partly overlain by a clastic succession of probable Ordovician age which wedges out eastward.

All these rocks, with the exception of the probable Ordovician clastics of the Mirbāt area, were maturely eroded and peneplaned so that the Mesozoic sediments transgressed onto this mature surface quite extensively. The lowest Jurassic sediments were clastics of Early and Middle Jurassic(f) age; this phase was soon replaced by deposition of neritic carbonate of Late Jurassic age which locally gave place to evaporites before the Jurassic Period ended with widespread deposition of carbonate, followed by block faulting, uplift, and erosion. The Jurassic rocks are exposed in the southwestern part of the area and extend into W.A.P.; they are brought up as salt domes in the western part of the E.A.P. and parts of Bayhān (W.A.P.) and eastern Yemen. Jurassic rocks are absent from a broad north-trending belt running through Al Mukallā, as well as from Dhufar (with the exception of some clastics). They were probably removed from some of the Al Mukallā belt by erosion prior to the Cretaceous and in other areas probably never were deposited, as would seem to be true in most of Dhufar. Elsewhere, Jurassic rock exposures are limited by the thick Cretaceous and Tertiary cover in coastal Al Mahrah.

Cretaceous sedimentary rocks are exposed over most of the territory and in coastal Dhufar, and can be seen wherever faulting or erosion of the Tertiary blanket has been sufficiently strong. They are primarily clastic in Ḥadramawt and into W.A.P., primarily carbonate in Al Mahrah to the east, and occupy an in-between position in western Al Mahrah Eastern Ḥadramawt, as also appears to be true in Dhufar. The age range is from Barremian to Maestrichtian.

The Tertiary sedimentary strata blanket most of south Arabia and range in age from Paleocene to middle Eocene; Oligocene and Miocene strata are more restricted in occurrence. In the E.A.P. the Paleocene is entirely a carbonate succession, but the lower Eocene shows intercalations, first of shales and then of evaporites, over a wide area; the middle Eocene shows a return to carbonate deposition with shale intercalations before regional uplift took place in the upper Eocene. In the eastern part of the E.A.P. and in Dhufar, carbonate deposition extends well into the lower Eocene, to be followed by evaporites and then more carbonates and fewer shales in the middle Eocene. Oligocene and Miocene deposits occupy restricted areas in present coastal regions, having been deposited in embayments in the coast. They are heterogeneous deposits in Ḥadramawt, ranging from coarse clastics to carbonates and evaporates, and in Dhufar they are thick chalky limestone and chalks succeeded by Miocene clastics and reef deposits.

Beach deposits, river terraces, and lacustrine and eolian deposits mark the termination of the Tertiary throughout the area and the start of volcanicity in coastal E.A.P. that persisted locally to Recent times.

The broad geomorphic expression of the territory has already been discussed in the preceding geographical sections and the influence of structure on morphology has been mentioned.

MAJOR UNCONFORMITIES

Several major time gaps are present; some are of striking clarity in the field and some are determinable by faunal examination only. These are dealt with in detail in the stratigraphic descriptions but are briefly summarized here.

Within the basement groups, several unconformities are probably represented. A major unconformity exists between the basement rocks and the Jurassic sedimentary rocks, and probably represents more than one erosion phase spanning a time gap from early Paleozoic to Early Jurassic. The next major time gap is between Late Jurassic and Cretaceous; the terminal Jurassic was generally followed by block faulting and differential erosion and planation, with the result that in places some of, or all, the Jurassic is removed. It is most probable also that the basal Cretaceous (Neocomian) is absent throughout the area, though some of the unfossiliferous pre-Barremian clastics may be partly Neocomian. Within the Cretaceous an unconformity probably exists between the Cenomanian and Senonian, and it is likely that there is no Turonian in the region, though this is difficult to establish on a faunal basis.

Another unconformity without angularity occurs between the Upper Cretaceous and the Paleocene, but this is not a major time gap, as only part of the Maestrichtian was removed. The next major time gap is at the end of the middle Eocene when general uplift took place over most of the area. The more restricted Oligocene and Miocene deposits may rest on any of the older rocks exposed.

HISTORY OF SEDIMENTATION

Little is known of the sedimentation history of the Precambrian and early Paleozoic rocks, but the early intrusive and metamorphic phase was followed by a period of intense eruptive activity at the close of which a succession of clastic and carbonate rocks was deposited over much of the area. Intrusive activity probably accompanied and followed the eruptive phase, continuing into a period of powerful orogenic movements which folded the sedimentary rocks, and resulted in mineral reconstitution in most, and cleaved all rocks. Dike injection and granitic emplacement continued for some time as mature erosion and peneplanation of the base-

ment was taking place. The history of the periods from this time to the Jurassic is not known.

The Jurassic transgression appears to have come from the south and the basal clastics filled irregularities in the basement floor. During neritic carbonate deposition, the zone of maximum subsidence centered on Yemen, trending south to the Berbera area of Somalia. With the development of evaporites in restricted basins and simultaneous open-sea deposits, the zone of maximum subsidence shifted eastward to the E.A.P. During the Tithonian, Yemen slowly emerged while widespread carbonate deposits covered the E.A.P. Shallowing and emergence followed, accompanied by block faulting which divided much of the southern part of Arabia into major north-trending highs and lows that were differentially eroded. The land surface was then gently tilted eastward.

The Cretaceous transgression came from the east, spreading the seas over a planed or eroded Jurassic floor, and where this had been removed, onto the basement. The area of greater subsidence was in east Al Mahrah, and continental deposits were laid in the west in Yemen. Regressions and transgressions and pinch-outs within the Cretaceous were interrupted by local uplifts in the Al Mukallā area, Ra's Sharwayn, and other areas, and the Cretaceous ended with shallowing and some emergence to be followed by the strongly transgressive Paleocene. Again the transgression was from the east, and after some regression and local deposition of evaporites, general uplift led to the start of the present structural development of south Arabia. Tertiary sedimentation from the later Paleocene began to be influenced by this structural growth, the result being the formation of the biaxial Ḥaḡramawt area.

Plates 1, 2, 3, and 4 give a general picture of the broad sedimentation patterns, as reflected in isopachs, from the Jurassic to the Eocene uplift.

NOMENCLATURE

Nearly all the geological knowledge of the area has been acquired in the last four decades mostly in the period since 1947 (see p. H2-H3). Much of this very recent period has been one of revision and experimentation with nomenclature and correlation based on lithostratigraphic division of rock units. Revision of early work and an establishment of a system of nomenclature was achieved in 1948 as a result of R. W. Wetzel's and D. M. Morton's fieldwork, but subsequent fieldwork in new areas of the E.A.P. led to further revisions of nomenclature and correlation by the author, and the introduction of new names.

The nomenclature described in this account has been designed to incorporate and use published names from neighboring areas where these apply to the Aden Pro-

tectorate without much change, and to define new nomenclature for the area where correlation with neighboring countries is not straightforward. Thus, the lithostratigraphic units used here are intended to be of regional rather than local value, despite the fact that defined units from neighboring areas have not generally been carried through into the E.A.P. The new terms are used where facies changes are so great, and intervening unknown areas so wide, that the carrying of such units would not be justified. When more regional information becomes available, other revisions may be made.

PRECAMBRIAN AND PALEOZOIC ERAS

BASEMENT

The term "basement" is applied here to the exposed igneous, metamorphic, and sedimentary rocks that were folded, or in part metamorphosed, cleaved, jointed, faulted, and then peneplaned before the first (Jurassic) marine sediments were deposited in the territory. The majority of basement outcrops are concentrated in the southwest. These rocks range from Precambrian to Paleozoic, but determination of a precise age is impossible.

Relatively little work has been done in the field on the basement rocks as compared with work on Mesozoic rocks; the present account embodies the field observations and incorporates preliminary field and laboratory observations by Prof. K. C. Dunham. Description is restricted to the area east of long 48° E., with two exceptions, the Jabal Sawād Bā Quṭnī area immediately to the west of long 48° E. at about lat 14°28' N. and the Jabal ath Thaniyah area on the Yemen border at about lat 15°50' N., long 46°20' E.

Four principal types of basement rocks are exposed in this area of the E.A.P.:

1. A series of volcanic rocks: lava flows and associated tuffs.
2. A series of metamorphic rocks, primarily metasedimentary but including some metaigneous.
3. A series of virtually unmetamorphosed sedimentary rocks, which are considered to be equivalent to type 2.
4. Intrusive igneous bodies, major and minor, silicic to mafic.

All these rocks have been involved in tectonic movements and varied deformation prior to peneplanation.

The metamorphic rocks and unmetamorphosed sedimentary rocks of types 2 and 3 have been divided into groups and these into formations where possible.

GĦABAR GROUP

The Għabar Group has been divided into four formations, all consisting of unmetamorphosed or virtually

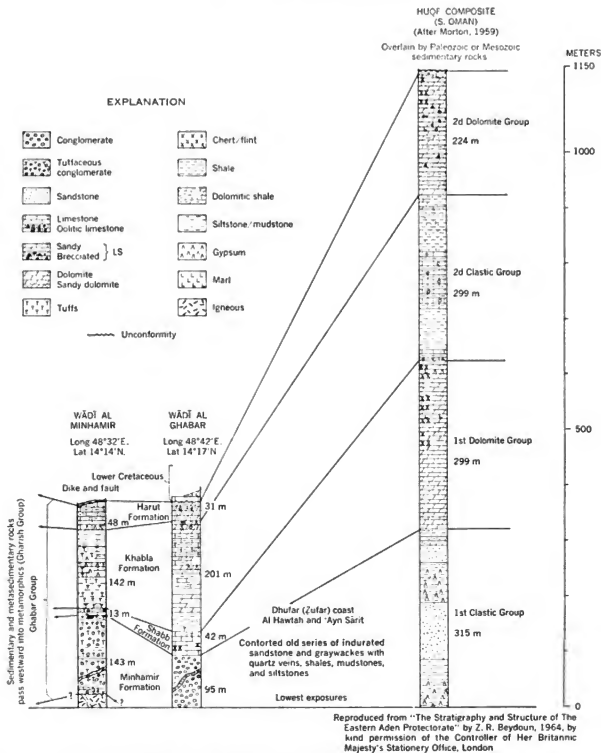


FIGURE 1.—Tentative correlation of Lower Cambrian (?) sedimentary rocks, from south Oman ('Uḡmān) to southwest Ḥadramawt (E.A.P.).

unmetamorphosed sedimentary strata. It crops out in two small areas in the eastern part of southwest Hadramawt, namely in the Wādī al Ghabar type area (lat 14°17' N.; long 48°42' E.), and in Wādī Minhamir (lat 14°14' N., long 48°32' E.) (Wādī Hajr basin). Figure 1 shows the formations of the two areas and correlation between them. A third subordinate area where the beds have been involved in small-scale thrusting (probably the cause of low-grade metamorphism to the greenschist facies) is in Wādī Bā 'Aryāf (lat 14°09' N., long 48°48' E.).

The formations of the Ghabar Group from base to top are as follows.

MINHAMIR FORMATION

At Wādī Minhamir the Minhamir Formation is 143 m thick; it consists of water-deposited lithic and crystal tuffs and some tuffaceous mudstone with pebbles of varying types of lavas, chiefly intermediate, but also with sparse metamorphic and cherty pebbles. Some dikes intrude. The Minhamir was probably formed from material eroded from a lava pile and deposited near at hand. There is no evidence that explosive activity was contemporaneous with deposition (K. C. Dunham, unpub. data, 1953-59). The formation rests on intermediate lavas, which form part of the Tha'lab Group; the contact appears to be disconformable.

In Wādī al Ghabar the formation is 95 m thick, and the base is not exposed. It consists of dull red tuffaceous limy conglomeratic sandstones with pebbles of crystal and lithic tuffs, silicified and calcareous tuffs, andesite, pyroxenite, diorite, porphyry, keratophyre, dolomite, chert, marmorized limestone, siltstone, and mudstone; granite and quartzite pebbles are sparse. Bedding and sorting of pebbles is evident and the formation is intruded by silicic and mafic dikes.

SHABB FORMATION

The Shabb Formation overlies the Minhamir Formation conformably and consists of platy, and thin-bedded, gray and pink limestones that are sandy in part and contain some chert bands along the bedding. In the Wādī al Ghabar section the formation is 42 m thick; at Wādī Minhamir the thickness is 13 m, and the limestone there encloses some gypsum. The formation is composed of chemical precipitates which represent the onset of an evaporation cycle.

KHABLA FORMATION

The Khabla Formation overlies the Shabb Formation conformably and gradationally, and the sequence at Wādī al Ghabar consists of 210 m of colored and gray dolomites and calcareous sandstones, siltstones, calcareous and dolomitic siltstones, some interbedded

dolomites, and some gypsum. In Wādī Minhamir the sequence is mainly tuffaceous or arkosic sandstone that is better sorted and poorer in lava fragments than the Minhamir Formation (K. C. Dunham, unpub. data, 1953-59), and it is 142 m thick.

HARUT FORMATION

The Harut Formation overlies the Khabla Formation conformably and gradationally, and consists at Wādī al Ghabar of well-bedded sandy dolomites, massive calcareous quartzites, and platy shaly beds with beds of impure dolomite and fairly pure limestone; a thickness of 31 m is preserved. At Wādī Minhamir the preserved formation is 48 m thick where it consists of gypsiferous, silty, and sandy limestones. The presence of gypsum and the rounding of sand grains indicates an arid environment and the onset of a second evaporation cycle.

The Ghabar Group in these two areas shows no metamorphism except near dikes; tectonic movements, apart from producing strong folding, have resulted in no apparent mineral reconstitution, but have imposed an intense multidirectional cleavage system on all the beds.

GHARISH GROUP

The Gharish Group is a series of sedimentary works and some lavas that have undergone regional metamorphism to the albite-epidote-amphibolite facies, reaching grades with garnet and staurolite as index minerals (K. C. Dunham, unpub. data, 1953-59); it occurs in the Wādī Garish-Jabal Madbī area of southwest Hadramawt (near lat 14°10' to 20° N., long 48°4' to 12' E.).

Several hundred meters is exposed, but the total thickness has not been measured and is probably considerable. The group, prior to metamorphism, consisted of tuffaceous conglomeratic beds, tuffaceous sands and shales, thin-bedded limestones, and arenaceous beds. A period of tectonic movements took place after deposition and led to strong folding (as for the Ghabar Group) and also to mineral reconstitutions of the sedimentary rocks of this group. Patchy amphibolites developed from pyroclastics, whereas (a) quartz, biotite, and muscovite schists, (b) hornblende, epidote, and chlorite schists, (c) variable phyllites, and (d) some quartzites developed from clastics with admixture of tuff. Interbedded phlogopite marbles represent persistent thin-bedded limestones. Squeezed volcanic pebbles in amphibolite indicate a tuffaceous conglomerate prior to metamorphism.

The presence of conglomeratic pebbles in this group and the persistence of thin-bedded well-defined calcareous beds, as well as the occurrence of quartzites, suggest that the Gharish Group is the same as the unmetamorphosed Ghabar Group cropping out some 40 km to

the east (p. H10-H11). Metamorphism increases westward from the latter owing to regional tectonic factors; greater alteration is favored also by the presence of more pyroclastic components, the purer calcareous units being comparatively less altered. Unfortunately the stages of lithological transition from the Al Ghabar-Minhamir sector westward cannot be followed in the field because they are masked by an intervening area of younger strata and are in part removed at the sub-Jurassic unconformity; however, the impression gained in the field is that one series is exposed in the two areas. Thus, in the Wādi Gharish area a correlation of the amphibolite with squeezed pebbles with the Minhamir Formation of the Ghabar Group is suggested, while the well-defined calcareous beds and calcareous beds with quartzite of the Wādi Gharish area can be correlated with the Shabb and Harut Formations of the Ghabar Group.

The Gharish Group has been invaded in several stages by major and minor igneous masses and by various dikes and sills. These have also contributed to alteration by contact-thermal metamorphism, which locally may have continued after dynamothermal metamorphism ceased, as indicated by the growth of porphyroblasts through the foliation.

THANIYA GROUP

The Thaniya Group is exposed in the extreme west of Ḥaḍramawt along the Yemen border in a number of disconnected outcrops (Jabal ath Thaniyah area, near lat 15°50' N., long 46°20' E.). The thickness is probably considerable; the upper part consists of some volcanics associated with dark quartzites, graphitic calcoschists, and thin-bedded phlogopite marbles of various types (Beydoun, 1960; unpub. data from the following: K. J. Ackerman, 1955, 1959; Fitch, 1955; Wells, 1955-56; and K. C. Dunham, 1953-59); these overlie thick-bedded calcareous rocks with chert bands. During a visit to Jabal ath Thaniyah, Geukens (1960) observed schists and quartzites which he mapped as Medina Series, overlain near the summit by younger crystalline limestone which he mapped as Jurassic (Geukens, 1960, pl. 8). No Jurassic has been found by the author, but Geukens' upper part may represent the equivalent of the Gharish and Ghabar Groups.

The Thaniya Group has undergone regional metamorphism to the albite-epidote-hornblende facies and has been invaded by dikes. Before metamorphism the rocks probably were various sandstones, siltstones, shales, limestones and dolomitic limestones, and associated lavas (unpub. data from the following: Ackerman, 1955, 1959; Fitch, 1955; and Wells, 1955-56).

The Thaniya and Gharish Groups are of about the same facies of metamorphism. While it is possible that

the two groups are lateral variants, it is believed that the former represents an older Precambrian sedimentation and that before metamorphism the Thaniya Group was probably the source of limestone, chert, and other pebbles preserved in the basal Minhamir Formation of the Ghabar Group to the southeast.

INTRUSIVES AND EXTRUSIVES

The basement intrusive and extrusive rocks of the Eastern Protectorate crop out mainly in southwest Ḥaḍramawt, though scattered exposures occur in the Jabal ath Thaniyah area and a relatively small exposure occurs at Ra's Sharwayn in coastal Al Mahrah (lat 15°20' N., long 51°37' E.).

Many of these exposures consist of extrusive rocks (The Tha'lab Group) which have been considered to be the oldest exposed rocks in this area of southwest Ḥaḍramawt (K. C. Dunham, unpub. data 1953-59; Beydoun, 1960). Intrusive rocks, both major and minor, generally postdate the extrusives though some are considered as possibly contemporaneous, and a few, of which only pebbles are now seen, probably predate the volcanic episode. The occurrence of these igneous bodies has been provisionally classified as follows.

The presence of sparse granitic pebbles in the basal Minhamir Formation of the Ghabar Group (p. H11) indicates that granite was undergoing erosion somewhere in the territory at the start of sedimentation of the Ghabar and Gharish Groups. This granite may be from an earlier intrusive which is no longer exposed, and is possibly contemporaneous with, though it more likely predates the older volcanics of the Tha'lab Group.

THA'LAB GROUP

Rocks of the Tha'lab Group were extruded during a widespread phase of volcanic activity, and consist of a thick series ranging from olivine basalt, through microphyritic pyroxene andesites and hornblende andesites to keratophyres and soda rhyolites; trachytes are scarce. Associated with the above are great quantities of pyroclastics ranging from fine-grained ashes to coarse and very coarse tuffs which include lithic, vitric, and crystal tuffs (K. C. Dunham, unpub. data, 1953-59). They constitute the remains of a very substantial volcanic episode; the vents through which these rocks were extruded have not been discovered. It appears that the volcanic suite of this group is predominantly of intermediate composition, namely andesites to keratophyres.

The extrusion of the Tha'lab Group mainly predated the deposition of the Gharish and Ghabar Groups, though some volcanic activity continued locally during the deposition of these two groups.

It is not known if the Tha'lab Group extrusion phase was contemporaneous with, or later than, deposition of the Thaniya Group; volcanics in the upper part of the Thaniya (p. H12) may belong to the same episode of volcanicity. It is suggested that the start of deposition of the Thaniya Group (and equivalent metamorphic rocks to the west in W.A.P.) preceded extrusion of the Tha'lab Group, but that sedimentation may have continued simultaneously with the extrusion of the Tha'lab Group.

During extrusion of the Tha'lab Group, intrusive activity probably also took place, but it is not known at present whether this consisted of major emplacement or was primarily restricted to dike injection.

Following the volcanic episode, and contemporaneous with the deposition of the Ghabar and Gharish Groups, intrusive activity continued. This apparently consisted of some major silicic emplacements into country rocks (Tha'lab Group) or granitization of the country rocks and the injection of dikes into the Ghabar Group; the dikes are restricted to the Minhamir Formation of the Ghabar Group in the Wādī al Ghabar sector. In the Kahtalih section (lat 14°18' N., long 48°40' E.) of the Wādī al Ghabar area, a silicic intrusion into the Tha'lab Group has resulted in a granite with partly digested fragments of Tha'lab volcanics. It is believed that from this body dikes were injected into nearby rocks of the Minhamir Formation.

A similar granite can be seen in the western edge of Jabal Jahmūm near Al Ma'ābir (lat 14°12' N., long 48°35' E.). Here also the emplacement is into rocks of the Tha'lab Group; aplite veins and dikes from the intrusion crisscross the country rock and the contact between the main intrusion and the country rock, and have resulted in the formation of hornfels.

Jabal Jahmūm also consists of a varied suite of intrusives including granodiorite and quartz and pyroxene diorites (Dunham, unpub. data, 1953-59). The igneous rock has a foliated "layered" appearance, and intrudes not only into the Tha'lab Group, but probably also into the Ghabar Group, a remnant of which is preserved to the southeast of the intrusion and which has been somewhat metamorphosed by the intrusion. The intrusion probably occurred in several stages, the last of which may postdate Ghabar Group sedimentation.

Jabal Sawād Bā Qutūl (near lat 14°27' N., long 48°45' E.) is a major granite emplacement. This granite intruded Gharish beds preserved at its eastern end, and isolated remnants (which may include some older metamorphic rocks) occur along its southern and northern edges. The intrusion has a foliated appearance and the Gharish beds (and older metamorphic rocks(?)) dip outward from it. The granite has undergone dif-

ferent degrees of cleavage, suggesting that the intrusion occurred in stages, the last postdating the phase of tectonic deformation. Both the Gharish beds and the intrusion are riddled with mafic dikes and sills, the latter following foliations (layering) in the granite and bedding in the Gharish Group. They probably belong to a later stage of igneous activity.

In the Wādī Gharish area, pyroxenites and pegmatites(?) as well as silicic and mafic dikes were probably intruded during this stage.

In the Al Mukallā district granite has been intruded into the Tha'lab Group, and aplite dikes finger out from the main body.

The intrusions and dike injections have imposed contact thermal metamorphism on the country rocks, but the extent of this is no longer clear because of subsequent regional metamorphism. It is reasonably certain, however, that intrusive activity during this phase occurred locally in several stages, some postdating sedimentation of the Gharish and Ghabar Groups, but predating the kinematic phase.

Major earth movements took place some time after the sedimentation of the Gharish and Ghabar Groups and associated igneous activity. During and at the close of this period, intrusive activity probably occurred, and some of the intrusions discussed previously, including the pegmatites, may have been emplaced at the time. The movements strongly and isoclinally folded the sedimentary rocks (and possibly folded some of the volcanic rocks) and imposed an intense multidirectional cleavage system on all rocks—sedimentary, extrusive, and intrusive. This process was accompanied (possibly in stages) by mineral reconstitution of some of the sedimentary rocks. Why some rocks underwent more reconstitution and deformation than others is not understood, but this may be attributed in part to regional tectonic factors which produced a higher grade of metamorphism from east to west, and to the presence of more pyroclastic components in sedimentary rocks to the west, enabling higher alteration to take place in that direction.

In at least part of the region rocks of the Tha'lab Group show little evidence of regional metamorphism other than cleavage and jointing, and yet they were able to coexist with sedimentary rocks showing metamorphism to the greenschist and higher facies.

Intrusive activity continued for some time. Granite emplacements postdating the period of earth movements took place, and dike injection was common. At Jabal Zulm ash Shaybah (lat 14°10' N., long 48°50' E.) a large granite cupola can be seen that effected thermal-contact metamorphism of the Tha'lab Group lavas. The granite does not show multidirectional cleavage,

but only normal rift and grain, which is considered to be postkinematic.

At Ra's Burūm (lat 14°18' N., long 48°49' E.), a large granite intrusion occurs in Tha'lab group volcanics; the granite here also shows normal rift and grain. One determination, by the potassium-argon method (N. J. Snelling, unpub. data, 1961-62), gave an age of 515 ± 25 million years.

Contact zones between these intrusions and the country rocks appear sharp and free from mixed rocks, but xenoliths of lavas included in the granite bodies have been extensively feldspathized. The granites in some places tend to be contaminated by constituents derived from xenoliths or country rock (Dunham, unpub. data, 1953-59).

At Ra's Sharwayn, R. W. Wetzel and D. M. Morton (unpub. data, 1948-50), observed a small outcrop of faulted and partly decomposed granite, having cleavage planes and containing quartz and pegmatite veins and dikes, intruded into or overlain by a folded series of metasedimentary rocks. Unfortunately it cannot be ascertained what relationship this granite bears to the metasedimentary rocks. However, an age of 467 ± 25 million years was determined from a pegmatite dike in this granite (Snelling, unpub. data, 1961-62, potassium-argon method). In view of the reported cleavage planes in the granite, it would appear to be prekinematic and therefore may be a remnant of an old intrusion more recently reactivated.

The strikes of folds and faults in the basement series are mainly north, trending a few degrees east or west of north; some also trend northwest, and less commonly, west-northwest and east-northeast. Strikes change direction abruptly in places, suggesting fault control (p. II45-II46), though in some places they are arcuate between two trends. The intensity of folding and its strike variation increases westward in the same direction as the increase in metamorphism.

Intrusions also tend to follow basement grains. For example, at the Jabal Sawād Bā Quṭmī intrusion, the sills and dikes strike approximately northwest to southeast, swinging to west-northwest with the strike of layering in the intrusive.

In Dhufar in the Mirbāt area, numerous dikes cut across the basement complex with north, northwest, and northeast trends and subordinate intermediate directions (Lees, 1928; Fox, 1947; Wetzel and Morton, unpub. data, 1948-50; Beydoun and Greenwood, 1966).

REGIONAL CORRELATIONS AND AGE

Evidence as to the regional correlation of the basement rocks of the E.A.P. is vague and conflicting. This has already been summarized by the author (Beydoun, 1960, 1964), but some reappraisal is given here.

In Somalia, the Inda Ad Series (of former British Somaliland), which is generally admitted to be very similar to the highest basement of the E.A.P. (Beydoun, 1960, 1964; F. R. S. Henson, unpub. data, 1954-60; Greenwood, 1961) has been referred alternatively to the Precambrian or the Paleozoic (Somaliland Oil Exploration Co., Ltd., 1954, summarizing earlier views). In south Oman an evaporite-clastic group assigned tentatively to the Lower Cambrian (†) (Morton, 1959) has been compared with the metamorphosed basement sedimentary rocks of the E.A.P. (Beydoun, in Morton, 1959; Beydoun, 1960, 1964; Henson, unpub. data, 1954-60).

The basement rocks of western Arabia have always been regarded as Precambrian in age. However, it is only in recent years that attempts to classify them stratigraphically have made some progress. Karpoff (1957, 1960) and Brown and Jackson (1960) place the youngest components of the basement complex in the late Precambrian. In the absence of paleontological evidence to the contrary, most geologists agree with this conclusion which recognizes the importance of the widespread peneplain at the base of the overlapping Cambrian and Ordovician sedimentary rocks in Saudi Arabia and Jordan. A minority view holds that the highest basement sedimentary and other rocks of western Arabia may be of an early Paleozoic age.

For the present there is no conclusive evidence to support or disprove these opinions. However, it may be useful to review some regional observations and suggestions which may serve as a basis for further investigation by others.

In the Al Kawr area of the W.A.P., extensive exposures of intrusive and metamorphic rocks occur. These have been described by Wissmann, Rathjens, and Kossmat (1942, p. 281-284), who remarked that "an upper less metamorphic mass of strata is distinguishable from a lower mass, but no unconformity can be discerned between the two."

Greenwood and Bleackley (1966) have mapped a large area of Precambrian metamorphic rocks in the W.A.P. that consist variably of schist, gneiss, quartzite, chert, crystalline limestone, and granulite, which are no doubt in part equivalent to the Thaniya Group of the Jabal ath Thaniyah area and the gneiss-granite rocks and schists of the area to the north. These would also be partly equivalent to what has been described as the Medina Series in Yemen (Geukens, 1960). These Precambrian metamorphic rocks of W.A.P. extend eastward into the Wahidi State almost to long. 47°50' E. in the Jabal Sawād Bā Quṭmī area. It is likely that some of them may be equivalent to the Gharish Group and therefore younger (Wissmann and others, 1942),

but this is not possible to establish with the present state of the mapping.

At Ra's Sharwayn, R. W. Wetzel and D. M. Morton (unpub. data, 1948-50; see p. H14) observed a folded and peneplaned series of metasedimentary rocks (50 m) which consists of quartzitic and micaceous sandstones laterally associated and interbedded with mica schists. This sedimentary series could be of the same age as the Gharish Group or it may be older.

In Dhufar at Al Hawtah and 'Ayn Sārit (Beydoun, 1960, 1964; Wetzel and Morton, unpub. data, 1948-50) limited exposures of varicolored indurated graywacke sandstones, quartzites, and shales resemble the upper part of the Ghabar Group in the E.A.P. These rocks were derived from a silicic igneous or metamorphic terrain (K. J. Ackerman, unpub. data, 1955, 1959). The series is of unknown thickness (estimated at Al Hawtah as 3,000 m without taking into account any repetition in the monotonous sequence) and has been highly folded, intensely cleaved, veined with quartz, and peneplaned. No dikes were observed. This series is overlain unconformably by Mesozoic sedimentary rocks.

A more highly metamorphosed basement, cut by many dikes, appears farther east at Mirbāt in Dhufar and in the Kuria Muria Islands as described by Lees (1928) and Fox (1947). Its composition at Mirbāt seems to differ little from that of the higher grade metamorphic rocks of the Aden Protectorate, and it is likely that the sediments of Al Hawtah and 'Ayn Sārit could have been derived from it. At Mirbāt intrusive bodies occur in the metamorphic series, among which are pegmatite and aplite injections followed by basic dikes; quartz veins are common (Beydoun, 1964). The basement series here has been peneplaned and is overlain by the Murbat Sandstone (Lees, 1928), which has undergone no metamorphism or deformation except faulting and which in turn is succeeded disconformably by Cretaceous deposits. The Murbat Sandstone is of unknown date, but it is presumably later than the folded sedimentary strata of 'Ayn Sārit and Al Hawtah. It somewhat resembles the unfolded Lower Ordovician of South Oman (Morton, 1959; F. R. S. Henson, unpub. data, 1954-60) with which it is here tentatively correlated. Farther east-northeast from Mirbāt toward Ra's Naws, the Murbat Sandstone has wedged out and Cretaceous rocks directly overlie the basement peneplain (Wetzel and Morton, unpub. data, 1948-50; Beydoun, 1964).

In Oman igneous basement rocks crop out only in the vicinity of Ra's al Hadd (Lees, 1928; Morton, 1959), but pre-Ordovician sedimentary rocks crop out along the Al Huqf-Hawshi swell (Morton, 1959). These include basal sands probably derived from silicic igneous

or older quartzite sources without a high-grade metamorphic component. Overlying the sands are evaporitic platy limestones and dolomites containing stromatolites, followed by a second sequence of clastics and an upper sequence of platy limestones and dolomites. This series compares closely in lithology and succession with the nonmetamorphic basement of southwest Hajar-mawt, namely the Ghabar Group, although the beds in Oman are thicker, devoid of pyroclastic components and are only locally folded. They are cut by quartz veins and mafic dikes which also occur in the basement of Dhufar, but so far are unknown in the overlying Ordovician of Oman.

These pre-Ordovician rocks of Oman have been assigned provisionally to the Lower Cambrian on the grounds that their evaporitic upper part may represent the beginning of a cycle completed in the "Hormuz Salt Series" (Middle and Upper Cambrian) which exists down the regional dip to the west (Morton, 1959). The salt series is missing at the outcrop where thick Lower Ordovician to Upper Cambrian clastics transgress over the eroded Lower Cambrian(?). However, the assumed continuity of the latter with the Hormuz salt is strongly supported by direct evidence in deep borings and by the discovery of *Linguella cf. L. nicholsoni* in salt pseudomorphs at the base of, and in apparent continuity with, the Lower Ordovician, which suggest transition downward to evaporitic Upper Cambrian which may occur in basinal environments (Henson, unpub. data, 1954-60; Beydoun, 1964).

The debris brought up by the Hormuz salt plugs in Oman and adjacent areas (O'Brien, 1957) includes platy limestone and dolomite with rare stromatolites, elastic rocks, gypsum, tuffs, and intrusive and extrusive silicic and mafic igneous rocks in various combinations. No volcanics have been found in later Paleozoic sedimentary formations of the Cambrian salt-dome areas.

It is suggested that in south Oman intra-Cambrian epeirogenic movements occurred after deposition of the Lower Cambrian(?) dolomite and limestone and prior to the Ordovician transgression, upwarping the Al Huqf-Hawshi swell and probably partly isolating basins to the west and north in which the Hormuz salt was deposited (Henson, unpub. data, 1954-60). These same movements, increasing in intensity to the west, may have been responsible for the folding of the highest basement rocks of Dhufar and the E.A.P. A phase of igneous extrusion on a small scale followed in south Oman (Morton, 1959; Henson, unpub. data, 1954-60).

In western Arabia (Al Hijāz), Karpoff (1957, 1960) recognized a "Wadi Medina Series" which includes lava, tuff, schist, quartzite, gneiss, conglomerate, and migmatite, overlain unconformably by a "Wadi Fatima

Series." This latter series has a basal conglomerate and includes sandstone, shale, lava, tuff, and laminated limestone with stromatolites. It is tempting to correlate it with the Ghabar and Garish groups of the E.A.P., although algal remains have not yet been found in the latter area.

Brown and Jackson (1960) recognized the Wadi Fatima Series, ranking it as a formation, and correlated with it their Abia Formation which crops out near Najran near the northeast border of Yemen. Their Fatima and Abia Formations rest unconformably on an older Murdama Formation (possibly equivalent to the Medina Series of Karpoff) and on a calc-alkaline granite series. They are overlain by the "Shammar rhyolite and andesite flows and tuffs, and tuffaceous sediments," and are intruded by the "Eastern Granite." The Fatima Abia, and Shammar Formations and Eastern Granite Group are given an age range of about 600-640 million years, based on the rubidium-strontium ratio in biotite from two samples from the Eastern Granite (Brown and Jackson, 1960).

Geukens (1960) grouped the majority of the basement rocks of Yemen into the "Medina Series" and remarked that the metamorphic rocks are intensely folded and generally strike north-south; during this period important granite bodies were emplaced. He recognized an unconformity between the Precambrian Medina Series and a less intensely folded "Fatima Series" preserved only in north Yemen and consisting of conglomerate and metamorphosed arkose passing into quartzite. The folds in general trend east. This Yemen Fatima Series marks a transgressive phase over the peneplaned top of the Medina Series. Geukens regarded its age also as Precambrian.

The upper Shammar unit of west Saudi Arabia is vestigial or missing in the E.A.P. Henson (unpub. data, 1954-60), however, believed that its presence before penetration is suggested by the abundance of dikes penetrating the upper basement formations (Gharish Group and others).

In Somalia, the Inda Ad Series as described by Mason and Warden (1956) rests unconformably on the basement complex. The basal part contains sandstone and a conglomerate with pebbles of the basement complex; the series is only dynamically metamorphosed, but sedimentary structure is well preserved. Above the conglomerate is a series of mudstones with siltstone and limestone bands, overlain by variegated mudstone and graywacke, in turn overlain by sandstone, grit, and conglomerate which are intraformational. The Inda Ad thus bears close overall similarity to the Ghabar Group of the E.A.P. (p. 119). A series of pelitic (phyllite, schist and metamorphosed limestone) and associated

volcanic rocks occurs in the Erigavo district; locally these differ only slightly from the cleaved mudstones of the Inda Ad, but they have been regionally metamorphosed—chlorite to hornblende facies (Mason and Warden, 1956). These metamorphic rocks are unlike the basement complex beneath the Inda Ad and bear general resemblance to the Gharish Group of the E.A.P., which is considered equivalent to the Ghabar Group (p. 119).

Greenwood (1961) questioned Mason and Warden's evidence for a younger Inda Ad resting unconformably on the basement complex and regarded their basal conglomerate as one of the interformational ones. Considering the other evidence available, he suggested that the rocks of the Inda Ad grade westward into the basement complex, the gradation from little-altered sedimentary strata in the east to the complex of metamorphic and igneous rocks in the west being brought about by intensification of metamorphism and igneous activity, the nature of which is regional. This proposed relationship does not invoke an unconformity. He further stated that if it is assumed (a) that the Inda Ad and basement complex of Somaliland are two expressions of a continuous series and (b) that the Inda Ad is Lower Cambrian—by correlation with the E.A.P. Ghabar Group and the Oman sedimentary rocks—then at least part of the basement complex must be of the same age, and this would be somewhat startling. He admitted that until more conclusive evidence is obtained alternative interpretations are possible.

So far isotope-age dating has contributed only slightly and indirectly toward a solution to these problems. Apart from the figures quoted by Brown and Jackson (1960) for west Saudi Arabia, a sample of muscovite-bearing pegmatite from the Gharish Group of the E.A.P. has been analyzed by D. York at Oxford University (unpub. data, 1960). This sample from the Wadi Gharish area at lat 14°08' N., long 48°12' E. indicates an age of 590 ± 50 million years (potassium-argon method). The pegmatite is younger than its host rocks, but it is thought to have been associated with the orogenic or post-orogenic magmatism which probably accompanied, and certainly followed, the folding and metamorphism (p. 1113). Metamorphism probably occurred in stages but in the course of a major orogenic cycle.

Another sample of muscovite from a pegmatite collected in the W.A.P. (area north of Aden) by Heybroek has been analyzed for Schürmann, and indicates an age of 545 million years (potassium-argon method) (Schürmann, written commun., 1961).

The only other dates so far available are from the younger granites, determined by N. J. Snelling (see p.

H14), which indicate that igneous activity took place in the lower Paleozoic.

An age of 590 million years for the Wādi Gharish pegmatite would indicate either (a) that the Gharish Group basement rocks of the E.A.P. are of late Precambrian age which would extend the age for the base of the Cambrian slightly upward, or (b) that the younger basement rocks are of Early Cambrian age. The problem must remain unanswered for the time being.

The prior review is perhaps too full of assumptions to prove anything. Nevertheless, it shows that there is some reason for considering a younger age than Precambrian for some basement rocks in parts of Arabia. The fact that their surface is peneplaned should not be the criterion for assigning them automatically to the Precambrian.

Until further isotope-age determinations for the E.A.P. basement rocks are made, little more can be said of the age of the basement rocks of that area.

ECONOMIC ASPECTS

Surprisingly few occurrences of economic minerals have been discovered in the basement areas of the E.A.P. What has been discovered does not appear to be of commercial value, being mainly limited to occurrence of iron in dikes or mineralized veins in areas of difficult access or too far from seaports. Some scattered occurrences of other minerals, including traces of galena, some mica (here of no commercial value), and small garnets are of no economic significance. It must be pointed out, however, that no systematic mineral survey of the area has been made. Such a survey may yield some results, but they will probably be limited, to judge by the overall picture so far known.

MESOZOIC ERA

JURASSIC SYSTEM

The oldest sedimentary rocks directly overlying basement are of Jurassic age. They are exposed in the coastal mountain belt of southwest Ḥaḍramawt west of long. 48°38' E. They reappear eastward in Al Mahrah at Ra's Sharwayn and probably at Al Masilah, although in the latter locality no diagnostic fauna is present in the part assigned herein to the Jurassic.

Two types of Jurassic rocks are recognized in the E.A.P. The first is the complete sequence exposed in the coastal areas, which is an open-sea sedimentation sequence. The second, incompletely exposed, occurs in the inland salt-dome areas; its lower part is an evaporitic sequence deposited in restricted basins or seas, and its upper part is an open-sea sedimentation sequence.

The Jurassic of the E.A.P. and the adjacent W.A.P., on the basis of abundant faunal evidence, is mainly Upper Jurassic in age. The basal part, a sequence of clastics without any fossils, is believed to be Middle Jurassic to possible Early Jurassic in age.

The formations which make up the Jurassic of the area are as follows:

Age	Group	Coastal areas (see pl. 2)	Salt-dome areas (see pl. 3)
Cretaceous to Tertiary	Astrak Group	Nafis Formation	Nafis Formation
		Mabli Formation	Shakh Formation 'Aysat-M'qash Member Layalim Member Shabwa Member
		Sitqra Formation	Unexposed
Middle to Lower Jurassic		Kohlan Formation	Unexposed
		Unconformity: Peneplanation— Basement (volcanic and meta-sedimentary rocks and granite)	Unexposed— Unexposed

KOHLAN FORMATION

The Kohlan Formation constitutes the basal unit of the Jurassic succession in the area. The name Kohlan was first applied (Lamare and others, 1930) for a similar succession exposed in Yemen in the Kuhlān area northwest of Ṣan'ā', where it consists of marls with sandstone and conglomerate layers that contain basement fragments succeeded by sandstone and interbedded sandstone and sandy marl that contain plant impressions. The whole succession reaches a maximum thickness of about 200 m.

In the E.A.P. (and the W.A.P.) reference sections have been taken from all well-exposed sections. The formation consists of a sequence of arkosic sandstones with several conglomeratic horizons which have variable-sized pebbles of vein quartz and igneous and metamorphic rocks; interbedded green and purple bands of marl, siltstone, and shale occur at various levels. The formation unconformably overlies peneplaned basement rocks and is current bedded; the sandstones are generally soft and friable, though bands of indurated ferruginous blocky sandstone occur. The upper part grades into the overlying Shuqra Formation, generally passing upward from sandstone, through silty marl to calcareous sandstone and sandy limestone. There is no evidence of any break between the two formations. The overlying Shuqra Formation, on the basis of fossil evidence, is Callovian to early Oxfordian in age.

Thus, the gradational contact between the Kohlan and the overlying Shuqra indicates continuity of sedimentation between the two, and suggests that at least for the

upper part of the Kohlan the age is probably Middle Jurassic. The lower part may be partly Early Jurassic and even Triassic, though Triassic is more unlikely in view of the comparative thinness of the formation and the overall type of lithology, which do not suggest accumulation over too long a period of time. No fossils or plant remains have been found in any part of the Kohlan in the E.A.P.

The formation is present in all completely exposed Jurassic sections of the E.A.P. and it everywhere underlies the Shuqra with gradational contact between the two. Thicknesses measured range between 17 and 81 m, the average being about 55 m. These variations are due to irregularities in the peneplaned basement surface on which the Kohlan Formation has transgressed, and to the persistence of scattered local highs in the basement during deposition of the Kohlan. The basement surface often shows a weathered rotted reworked upper few meters on which the Kohlan rests, and it may be composed of volcanics, granite intrusives, or steeply tilted and truncated metasedimentary rocks. Weathered and reworked volcanics show bedding parallel with the overlying Kohlan; examples of tilting of the basement with the overlying Jurassic are fairly common.

The Kohlan Formation shows marked uniformity in overall lithology, as interbedded siltstone, marl, and shale layers are almost everywhere present within the sandstone; conglomeratic zones are ubiquitous. The Kohlan's color is generally light—white and pink. It weathers gray to light brown, and is easily distinguishable from similar clastic formations of Cretaceous age because of this. In one section at Jabal 'Atāq, a very thin limestone occurs near the base of the Kohlan, interbedded with marl and siltstone within the sandstone.

AMRAN GROUP

The formations of Late Jurassic age have been grouped together under the name Amran Group (Cretaceous to Tithonian). The Amran Group in the E.A.P. and W.A.P. embraces all exposed formations of Jurassic age occurring above the Kohlan Formation.

The name Amran was first used (Lamare and others, 1930) to describe Jurassic deposits occurring above his Kohlan Series in Yemen. The type locality of Lamare's Amran Series is the 'Amrān area of Yemen, northwest of San'a'. Paleontology has been discussed by Basse (1930). Rathjens and Wissmann (in Wissmann and others, 1942) also examined a similar section in the same general area, and Karrenberg (in Basse and others, 1955) sampled an incomplete section nearby.

The Amran Group in the E.A.P. varies appreciably in thickness in the coastal exposures. This is in part due to sedimentation, but it is also in part due to ero-

sion. A maximum measured thickness for the group is 733 m, and a minimum preserved thickness of 35 m has also been measured.

In Hādrāmawt, exposures occur west of long. 48°38' E. Generally speaking, in the area immediately west of this longitude, the thinnest part of the group occurs, thickening westward to the maximum at Jabal Madbi (lat 14°17' N., long 48°04' E.), then thinning again, but only slightly, westward into the W.A.P. East of long 48°38' E. the group is absent, reappearing again in Al Masilah (no faunal evidence) and at Ra's Sharwayn in coastal Al Mahrah. Eastward and northeastward from these localities it disappears, being absent in Dhufar and also in Socatra to the east-southeast.

In the coastal type of sequence, the group is a marine open-water succession of limestone and marl facies. The lower part is a neritic shallow-water limestone and marl facies (Shuqra Formation), followed by a more open-sea marly facies (Madbi Formation), grading into an argillaceous limestone facies which in turn grades into and terminates in a shallow-water marly sandy facies (Naifa Formation). Inland, in the salt-dome sections, the lower part of neritic limestone facies (Shuqra Formation) is not exposed, but it is presumed to be present below the evaporites, which are the lowest beds exposed. The evaporites were deposited in restricted basins or seas and make up the Sabatāin Formation which is correlated with the more open sea Madbi Formation as a lateral variant (see p. H120). Overlying both the Sabatāin Formation and the Madbi Formation is the Naifa Formation, indicating the spread of open-sea conditions inland and the end of restricted deposition. The Naifa Formation is present in all Jurassic coastal and salt-dome sections in the E.A.P. that have not undergone sufficient erosion to remove it.

In its uppermost part the Amran Group is possibly lowermost Cretaceous (Berriasian) (M. Chatton, unpublished data, 1948-50) in the western part of the coastal area of Hādrāmawt, but this possibility is limited to a few sections where macrofaunal evidence is poor and suggests affinities with Berriasian.

A marked unconformity with little or no angularity at the top of the Amran Group, but which may occur at various levels, indicates a period of emergence and plantation prior to the Cretaceous transgression proper.

COASTAL SECTIONS

Shuqra Formation

This Shuqra Formation is present in all Jurassic sections in Hādrāmawt, in the W.A.P., and in the Ra's Sharwayn section of Al Mahrah. In Hādrāmawt it is between 60 and 80 m thick, though as little as 39 m has

been measured as a full succession not reduced by erosion in the easternmost exposures of Hadramawt.

The name Shuqra Limestone was first used by Heybrook (in Hudson, 1954) for the sequence of limestone sampled by him near Shuqrah in the W.A.P. This section was later sampled by R. W. Wetzel and D. M. Morton (unpub. data, 1948-50) where some 98 m of well-bedded limestone, abundantly fossiliferous and including some rubbly and marly zones overlies 20 m of sandstone. The top of the limestone is not seen as it is overlain by a sub-recent lava flow. Farther to the north in the W.A.P. a more complete section of Upper Jurassic (Amran Group) is exposed.

In southwest Hadramawt, Upper Jurassic reference sections are well exposed and the Shuqra Formation is divisible into the following units in many places:

1. A basal interval of well-bedded neritic limestone, generally sandy at the base and sometimes at higher levels, detrital and commonly oolitic and containing interbedded rubbly marls; fossiliferous.
2. A 7- to 10-m interval of very fossiliferous rubbly yellowish marl.
3. Sequence of well-bedded limestone as in unit 1.
4. A terminal 5- to 10-m interval of fossiliferous rubbly marl as in unit 2.

The top interval may be absent in some sections in southwest Hadramawt. Where this happens, the overlying Madbi Formation rests directly on unit 3, indicating either a disconformity or a lateral extension upward of the limestone of unit 3 to replace the marl of unit 4.

At Ra's Sharwayn, the Shuqra is about 56 m thick and consists of 36 m of fossiliferous limestone and marl bands and an upper 20 m of fossiliferous marl. Apart from this locality the formation is not exposed elsewhere in Al Mahrah.

In the field there is an apparently conformable contact with the overlying Madbi Formation, but the absence of the uppermost rubbly marls of the Shuqra in some sections would seem to indicate a local disconformity.

The rich faunal assemblage has already been partly described by Hudson (1954) from the collections from Jabal al 'Urays near Shuqrah in the W.A.P. and from Ra's Sharwayn in Al Mahrah. In the assemblage from these sections and from the sections in southwest Hadramawt, the following fauna occur (Hudson, 1954; unpub. data from the following: Hudson, 1948-56; Gosling, 1956; Cox, 1949-56; Chatton, 1948-59; Elliott, 1951-59; and Spath, 1955-57):

Rhynchonella hadramautensis Stefanini, *R. aff. R. moriere* Dav., *R. hudstonei* Roll., *Sonulirhynchia afri-*

cana Weir, *S. wetzeli* Hudson, *S. tumida* Muir-Wood var., *S. bihendulensis*, *S. africana* var., *swellii* Weir, *S. cf. S. somtica* (Daque), *S. bihenensis*, *S. africana* var., *jordanica*, *Terebratulina bisuffurcinata* Schlotheim, *T. subella* s.l., cf. "*T.*" *subella* Leymerie, cf. *T. zeiteni* de Loriol, "*T.*" *aulica* Stefanini, "*T.*" cf. *T. suprajurensis*, *Dagbonichynchia hadramautensis* (Stefanini), *D. cf. R. cf. moriere* Stefanini, *D. subversibiles*, *D. daghaniensis* var. *platiloba*, *D. daghaniensis* var. *elongata*, *D. daghaniensis*, *D. macfadyeni*, *D. kabietensis*, cf. *D. farquharsoni* Muir-Wood, "*D.*" *platiloba* Muir-Wood, "*Burwicheynchia*" *gregori* Weir, *Sonulirhynchia bihendulensis* Muir-Wood, cf. *S. macfadyeni* Muir-Wood, *Chaltonithyrus bihenensis* Weir, *Cerithiuthyrus somaliensis* Weir, *Lophrothyrus sentia* Muir-Wood, cf. *L. Ptyctothyrus daghaniensis* Muir-Wood, *Striithyrus somaliensis* Muir-Wood, *Trigothyrus crudueensis*, *Sphacrodithyrus browni*, *Zeillerina latifrons* (Krumbeck), *Ecocollista krenkeli* Cox, *Ceromyopsis arabica* Cox, *C. striata* d'Orbigny, *C. eocenica*, *C. somaliensis* Weir, *Pholadomya aubryi* Douville, *P. lineata* (J. de C. Sowerby), *P. protei* DeFrance, *P. (Homomya) inornata* J. de C. Sowerby, *Lima (Plagiostoma) harronsi* Daque, *Lophia solitaria* (J. de C. Sowerby), *L. gregaria* (J. Sowerby), *L. costata* (J. de C. Sowerby), *Mytilus (Modiolus) inabricatus* (J. Sowerby), *Nerinea somaliensis* Weir, *Aulacomyella* cf. *A. similis* (Munster), *Astarte (Coelastarte) acyalis* Holdaus, *Paralledon egertonianus* Stoliczka var. *crebricostatus* Stefanini, *Gryphosia balli* (Stefanini), *Eozogrypha fourtani* Stefanini, *E. cf. E. nana* (J. de C. Sowerby), *Macromya aequalis* Agassiz, *Ceratomya winamensis* (Gillieron), *Musculus somaliensis* Cox, *Eligmus analites* (Stefanini) *E. Weiri* Cox, *Graunmitodon (Indogranitodon) egertonianus* (Stoliczka), *Stylina macfadyeni* Thomas, *Amphistrea gibberosa*, (Gregory), *Astrocoenia newtoni* Gregory, *A. Bernensis* Koby, *A. cf. A. Hypodaidema macfadyeni* Currie, *Belonopsis tangerensis* (Futterer), *Sutneria* aff. *gular* (Oppel), *Shuqraia zuffuriae* (Wells), *S. heybroeki* Hudson, *S. arabica* Hudson, *S. cf. S. Stromathopora douvillei* Dehorne, "*Stromatopora*" *harrarensis* Wells, "*S.*" *kurtcheni* Wells, *Milleporidium somaliense* Zuffardi-Comerci, *Pseudorychnium* cf. *P. scapula* Mohler, *Nautiloculina colthici* Mohler, *Trocholina palastinensis* Henson, *Favulicella jussica* Henson, *Pfenderina* sp., *Salpingoporella annulata* Carozzi, *Cylindroporella J. 1.*, and others.

This fauna establishes a Callovian and Argovian (Oxfordian) age for the Shuqra, though the uppermost part probably ranges into the Sequanian.

Madbi Formation

The Madbi Formation immediately overlies the Shuqra Formation and occurs in all sections of the Jurassic wherever it has not been removed by erosion in southwest Ijādamawt west of long. 48°38' E. The type section is chosen from Jabal Madbi. Generally, the formation is thinnest in the eastern part of southwest Ijādamawt where thickness of some 60–100 m are known, and it thickens westward to an observed maximum in the Gharish-Madbi area (maximum at Wādī Gharish, 290 m). Westward from there thicknesses range from 105 to 250 m, depending probably on the influence of scattered local highs that may have persisted for a while during sedimentation. The formation extends into the W.A.P.

In southwest Ijādamawt the Madbi consists of a series of marls, gray to dark gray and yellow, commonly shaly and in places silty, and locally gypsiferous; some sections contain thin gypsum beds. With the marls are interbedded thin bands of rubbly or marly limestone, in places detrital, and generally fossiliferous; bread-loaf-type concretions reaching half a meter in diameter are common at various levels, and the marls commonly are bituminous in their upper part.

In Al Mahrah the Madbi Formation is believed to be present only at the Ra's Sharwayn section (Beydoun, 1960, 1964) and is present there in a limestone facies with several marl zones capped by shale and marl; fossils are common, though nondiagnostic.

The lower and upper contacts of the Madbi Formation are apparently conformable in the field, though the lower contact with the Shuqra may possibly be locally disconformable (for example, Wādī Gharish section shows a hummocky surface at the top of limestone (unit 3) of the Shuqra (p. II19). The upper contact is conformable and locally gradational.

The formation is fossiliferous throughout its sequence in the Ijādamawt sections and thin lumachelle bands consisting of fossil debris are common at various levels. Among the faunal assemblage the following are present (unpub. data from the following: Hudson, 1948–56; Cox, 1949–56; Arkell, 1956–58; and Smout, 1953–59): *Gryphaea balli* (Stefanni), *Lophia marshi* (J. Sowerby), *L. cf. L. solitaria* (J. de C. Sowerby), *Eozogyr fourtavi* Stefanini, *Ostrea* (Liostrea) *wagurensis* Cox, *O. (Liostrea) cf. O. moreana* Buvignier, *Astarte (Coelastarte) scythalis* Høldaus, *Modiolus imbricatus* (J. Sowerby), *Inoceramus cf. I. suprajurensis* Thurmman, *Posidonia somaliensis* Cox, *Proconulus ambalensis* (Weir), *Terebratula cf. T. terebratula*, *Daghanirhynchia macfadanyi*, *Somalirhynchia africana* cf. *S. jordanica*, "*T.*" *awalites*, *S. africana* cf. var. *smelleti*, *Laevaptychus latus* (Parkinson), cf. *Atazioceras des-*

moides Wegele, *Idoceras* cf. *I. jarguhasoni* Spath, *Perisphinctes mombassanus* Daque, *P. (Pachysphinctes) robustus* Spath, *P. (Divisosphinctes) cf. P. inaequalis* (Spath), *Belemnopsis tangenensis* (Futterer), *Rhopala teuthis somaliensis* Spath, *Valvulinella jurassica* Henson, *Paleotrix* (form X), and others. From these a Kimmeridgian age is indicated, probably Sequanian to upper Kimmeridgian (lower Tithonian), but the lower limit may go down into upper Argovian (Oxfordian).

The Madbi Formation is equivalent to the Sabatani Formation inland in the salt-dome areas. This is indicated by the following: (a) the position of the Naifa Formation conformably overlying the Madbi in the coastal-type Upper Jurassic and the Sabatani in the salt-dome-type Upper Jurassic; (b) the presence of gypsum, locally in thin primary beds within the Madbi—indicating the advent of evaporitic conditions in the coastal areas—though much more common inland; and (c) faunal evidence, albeit rather meager, found in the Sabatani Formation. Regional correlations from Yemen support this view.

Naifa Formation

The Naifa Formation immediately overlies the Madbi Formation of the coastal Upper Jurassic and the Sabatani Formation of the salt-dome areas, and forms the top unit of the Amran Group. Its contact with the Madbi is conformable and gradational in a number of sections, and its contact with the Sabatani, preserved only at the 'Iyādh salt dome, appears conformable in the field.

The Naifa Formation type section is near Al Ma'abir in Wādī Hajr. The formation can be divided into two parts, upper and lower. The lower part consists of a sequence of thin-bedded fine-grained to porcellaneous limestone, with common thin zones of platy dolomite, dolomitic shale, rubbly marly limestone, or marl. This sequence is present everywhere, generally all of it being preserved, and ranges in thickness from about 50 m in the eastern part (immediately west of long 48°38' E.) to several times that thickness westward and to some extent northwestward. A maximum thickness for this lower part totaling 446 m was measured at Jabal Madbi, situated toward the center of the area of Jurassic outcrops of southwest Ijādamawt. Westward toward W.A.P., thickness is considerable though generally appreciably less than at Jabal Madbi itself.

The upper part of the Naifa Formation consists of a sequence of marl, generally gray and yellow but also pink, commonly shaly and in places gypsiferous or silty, and containing interbedded marly limestone, which is gray, rubbly to fissile, fine-grained, and locally shelly. Where the upper part is preserved, it is thicker in the

east than it is in the rest of southwest Hajarawt. A maximum thickness of 78 m for this part was measured at the Al Ma'abir section. The upper part is generally missing in the west, being partially recorded in only two sections where just 14 m in each is preserved. It is absent in the salt-dome areas.

In certain localities some of the upper part of the underlying thin-bedded limestone is also missing. This is due to a period of erosion late in the terminal Jurassic, which followed a phase of block faulting.

The significant thickening of the lower part of the Naifa Formation from east to west and the presence of a thicker upper marly sequence in the east than in the west may partly be explained by a lateral variation in facies; the upper part of the thin-bedded limestone in the west is probably equivalent to part of the upper marly sequence.

In three of the western sections, but especially well developed at Jabal Madbi, the thin-bedded limestone sequence has several conglomeratic zones in its lower part; these are largely conglomeratic limestone consisting of pebbles of Jurassic and some basement rocks in a limestone matrix, in places containing sandy layers. The conglomeratic zones grade into thin-bedded limestone, which are in places associated with platy dolomites and in the upper part with fetid and oily coarse limestone; at the Wadi Gharish section fetid shales, aragonite, and some marls are also associated. The maximum thickness of this conglomeratic member is in the Jabal Madbi section; it is less thick at Wadi Gharish, and even thinner at Jabal Sakha near the W.A.P. border. The conglomerates mark intraformational breaks within the Naifa Formation and are attributed to local erosion after slight intra-Jurassic uplift, though some may be due to penecontemporaneous slumping and reworking by currents in shallow-water conditions. In Wadi Gharish many of the pebbles are subangular and are more of a breccia than a conglomerate.

The presence of these intraformational breaks and the association of evaporitic beds with some of them at the start of the Naifa Formation sedimentation appear to indicate local erosion of a partial barrier erected during earlier intra-Jurassic movements. This isolated the inland salt-dome areas, giving rise to the Sabatani Formation there, while the equivalent Madbi "open sea" Formation was being deposited to the south. The erosion of this partial barrier during early Naifa deposition allowed this latter formation to extend inland over the salt-dome areas, and open-sea sedimentation then became general for both areas.

In southwest Hajarawt, the coastal sections in the eastern part are more fossiliferous than coastal sections

to the west. The latter have undergone more recrystallization, and the macrofauna found in beds in these sections are indeterminate. In general, the macrofauna is fairly well preserved in the marly and rubbly parts of the sequence, while that in the limestone is recrystallized. The occurrence of fauna is sporadic and varies from section to section; in some, extremely fossiliferous zones with abundant ammonites occur (for example, Naifa section in Wadi Hajar, also examined by Little, 1925).

From determinations on the fauna collected, the formation includes the following (unpub. data from the following: W. J. Arkell, 1956-58; L. F. Spath, 1955-57; R. G. S. Hudson, 1948-57; F. Gosling, 1956; M. Chatton, 1948-59; A. H. Smout, 1953-59; and E. K. Elliott, 1955-59): ?*Virgatosisimoceras* sp., *Perisphinctes* (*Pachysphinctes*) *robustus* Spath, *P. (P.) cf. P. granti* Spath, *P. (Dichotomosphinctes) cf. P. krapf* Dacque, *P. (D)* *cf. P. eggeri* von Ammon, *P. (Lithacoceras) cf. P. torquatus* Spath, *Planites* (*Biplicies*) sp. *cf. P. africanus* (Dacque), *P. cf. P. polygyratus* (Reinecke) of authors, *P. cf. P. anabreviceps* (Dacque), *Taramelliceras cf. T. trachynota* (Oppel), *Aspidoceras cf. A. longispinum* (Sowerby), *Atazioceras cf. hictor* (Fontannes), *Discoisphinctes cf. geron* (Zittel), *Physodoceras* (*Simaspidoceras*) aff. *P. argobae* (Dacque), *Laevaptychus latus* (Parkinson), *Lamellaptychus pleidensis* Trauth, *Belemnopsis tangensis* (Futrer), *Grammatodon* (*Indogrammatodon*) *egertonianus* (Stoliczka), *Proconulus arabiensis* (Newton), *Aulacomysella cf. A. farquharsoni* Cox, *Calpionella mollelloides*, *C. alpina* Lorenz, *Nannoceras cf. N. steinmanni*, *Pseudocyclammina* sp., *Macroporella gigantea* Carozzi, *M. Pygmaea* (Gumbel), and others. *Pseudocyclammina* sp. occurs principally in the western sections.

From the above faunal suite, a Tithonian age is indicated for the formation, but opinion varies as to whether it is between Lower and Middle or between lower and upper Tithonian. The presence of *Pseudocyclammina* sp. in a form similar to Lower Cretaceous forms from the Persian Gulf area led Chatton (unpub. data, 1948-59) to attribute a Tithonian to Berriasian age to the formation in Hajarawt, but the macrofossil evidence, lacking in the western sections, indicates that no Cretaceous is present.

In the salt-dome areas the Naifa Formation consists entirely of thin-bedded limestone with bands of platy or shaly dolomite and thin rubbly layers; some fauna has been found.

At Al Masilah in Al Mahrah is a sequence of some 116 m of limestone and dolomite (base not seen) overlain by 48 m of marl and shale with limestone and sandy

limestone containing *Cyclammina* sp. and indeterminate oysters and other pelecypods (R. W. Wetzel and D. M. Morton, unpub. data, 1948-50); it most probably represents the Naifa Formation, and underlies a thin conglomerate which probably marks the Jurassic-Cretaceous unconformity. The conglomerate is followed by 99 m of undated strata overlain conformably by Lower Cretaceous beds.

At Ra's Sharwayn a 50-m sequence of dolomitic limestone underlies a brecciated limestone interval and is overlain by datable Lower Cretaceous. The brecciated limestone is taken as evidence of unconformity (Chatton, unpub. data, 1948-59; Beydoun, 1960, 1964), below which the 50-m dolomitic limestone sequence is taken as representing the Naifa Formation.

SALT-DOME SECTIONS

Sabatatin Formation

The Sabatatin is the lowest exposed formation of the Amran Group in the salt-dome areas of west and north-west Iqdamawt (and the two adjoining salt domes at Al-'Ayādim (Layadim) in W.A.P. and Sāfir in Yemen. It is a restricted succession of evaporites with clastics; the basal part is everywhere salt followed conformably by a persistent interval of shales containing Late Jurassic fauna (*Anethozion* and others), overlain conformably by gypsum that laterally grades into clastics. The Late Jurassic age is confirmed in the Sāfir dome in Yemen (Geukens, 1960). The Sabatatin Formation is the lateral variant of the Madbi Formation in the south; facies differences between the two are due to separation during sedimentation by a partial or complete barrier that led to evaporitic conditions for the Sabatatin and open-sea deposition of the Madbi to the south. This barrier (or barriers) was subsequently removed during early deposition of the overlying Naifa Formation (compare conglomerates in the lower Naifa Formation indicating intra-Jurassic erosion) and allowed the Naifa Formation to spread over the salt-dome areas (p. H20-H21).

Alternatively, the rise of evaporitic conditions may have been partly or additionally due to the occurrence of submarine plateau conditions where stagnation with rapid evaporation prevailed in the absence of deep-water current circulation (Henson, in Fox, 1959).

In Iqdamawt the Shuqra Formation is not exposed below the Sabatatin in the salt-dome areas, but in Yemen both the Shuqra equivalent and the underlying Kholan are present, the former occurring below evaporitic beds. It is therefore strongly indicated that the Shuqra Formation lies below the Sabatatin in Iqdamawt.

The seven surface salt domes of the E.A.P. occur in three areas: (a) the Al Mīntāq area in the Wādī Hajar

basin, which is the most easterly and southerly occurrence of salt domes in Iqdamawt (lat 14°32' N.; long 48°02' E.) and includes Al Mīntāq, Jūbah, and Siyāl al Milh domes, (b) the 'Iyādhī area where the Hāyd al Milh ('Iyādhī) dome occurs (lat 14°59' N., long 46°49' E.), and (c) the Shabwah area, the most northerly of the three areas, where the Shabwah, Milh Kharwah, and Milh Maq'ah (M'qah) domes occur (lat 15°22' N. long 47°00' E.). Some 70 km west-northwest of 'Iyādhī, the Al 'Ayādim dome of Baylān (W.A.P.) occurs in the sands of Ramlat as Sab'atayn, and about 60 km north of that, the Sāfir dome in Yemen occurs also in the sands of Ramlat as Sab'atayn. No other surface expression of Jurassic salt domes is known from these three territories or from the neighboring countries.

The formation is variably exposed in these salt domes (the base is not exposed) from 62 m at Milh Kharwah to a maximum of 280 m in the 'Iyādhī dome. It is divisible into four members, two persisting in all the domes. The members occur as follows:

'Ayad Member intertonguing with M'qah Member
Layadim Member—persistent
Shabwa Member—persistent
Base not exposed

Shabwa Member.—The Shabwa is the basal unit and crops out in all salt domes examined; its base is not exposed and generally only the top 10-20 m is exposed. The unit consists of rock salt having layered structure, gray striations, and bituminous stains. In all domes the salt is conformably overlain by the Layadim Member. This and the fact that the dip of the beds in the Layadim Member is parallel to the dip of the salt layers have led to the postulation of a stratigraphic contact between the two and to the belief that the salt is depositional and not of piercement origin (R. W. Wetzel and D. M. Morton, unpub. data, 1948-50; Beydoun, 1960, 1964).

Layadim Member.—The Layadim is predominantly a shale unit, consisting of variegated shales, thin bands of marl, shaly limestone, dolomitic limestone, and some gilsonite beds; the shales are commonly black and papery, in places sandy, micaceous, and generally bituminous or carbonaceous. Laterally, in some domes, the unit becomes predominantly marly, though locally shaly, and contains salt streaks.

Thickness of the unit varies, being about 63 m in the Shabwah dome, but in some domes (for example, Al Mīntāq) as little as 7 m is present. The contact with the overlying unit (the 'Ayad or M'qah Member) is conformable. The Layadim Member occurs in all the domes in the same stratigraphic position and in the same attitude as the underlying Shabwa Member and

overlying 'Ayad or M'qah Member. Thickness and facies variations do not appear to alter its overall characteristics or its position in the succession.

Only in the Shabwah dome was any determinable fauna found in this member (Wetzel and Morton, unpub. data, 1948-50). This included the fish *Anaethalion*, and abundant *Esteria* and *Spongistroma*. On the basis of this, an Upper Jurassic age has been assigned to the Layadim Member (Beydoun, 1960; F.R.S. Henson, unpub. data, 1954-60; R. G. S. Hudson, unpub. data, 1948-56).

'Ayad Member.—The 'Ayad Member is one of the two top units of the Sabatani Formation, the other being the M'qah Member which forms a lateral variant of the 'Ayad. The 'Ayad Member consists of a series of white to yellow bedded gypsum with some interbedded thin bands of fetid dolomite, argillaceous and bituminous limestone, and limestone with phacoids. These bands vary from section to section, being absent in some places. The 'Ayad overlies the Layadim Member conformably. Its thickness varies, the maximum of 230 m being at the 'Iyadh dome. In most of the other domes, the member is incompletely preserved or absent owing to erosion, and only at 'Iyadh is it in actual contact with the overlying Naifa Formation. There, overlying limestone beds of the Naifa Formation dip conformably with the underlying gypsum of the 'Ayad Member.

M'qah Member.—The M'qah Member occurs in the Milh Ma'qah dome, and it is partly represented in the Shabwah dome as a tongue in the 'Ayad Member. The M'qah Member at the type section is about 150 m thick and contains some plant remains. It consists of coarse greenish ripple-marked sandstones that alternate with colored micaceous shales. Beds of shaly limestone, dolomite, and marl occur at various levels; gypsum is present at the base and top of the unit and in bands at various levels within the elastic sequence. Some beds are fetid and bituminous.

The M'qah Member, by its conformable position above the Layadim Member shales at the Milh Ma'qah dome and the intertonguing of its elastics into the gypsum of the 'Ayad Member at Shabwah, is shown to be a lateral facies variant of the 'Ayad Member. The indication is that lagoonal conditions developed in the northern part of the evaporitic basin, and that evaporitic conditions returned from time to time. Examination of the elastics suggests that they were derived from the basement of the Ath Thaniyah area to the west-northwest, which was undergoing erosion and supplying material into the evaporitic lagoonal basin of the Sabatani Formation. These lagoonal conditions persisted into parts of Yemen (Geukens, 1960).

Naifa Formation

The Naifa Formation has already been partly described (p. H20-H21). It is a formation common to both the conical and salt-dome areas of Upper Jurassic deposits, with almost identical facies in both, characterized by thin-bedded rather porcellaneous limestone. It has been found completely preserved at Al Mintāq dome where it is in depositional contact with the overlying Qishn Formation, the contact being marked by a thin conglomeratic sandstone. The sequence at Al Mintāq is 150 m thick and consists of thin-bedded limestone, bands of platy or shaly dolomite, and thin rubbly layers. Contact with the underlying 'Ayad Member of the Sabatani Formation is not exposed. At 'Iyadh 87 m of the formation is preserved and consists of thin-bedded fine-grained rather porcellaneous limestones, as in the Al Mintāq section. The top beds have been removed by erosion; the contact with the underlying 'Ayad Member of the Sabatani Formation appears conformable. The Naifa Formation is absent in the other salt domes (except Jūlah), having been eroded.

Some fauna has been collected from deposits in the Al Mintāq dome. This fauna, on the whole, is poorly preserved, but includes the following (R. G. S. Hudson, unpub. data, 1948-56; A. H. Smart, unpub. data, 1953-59): *Thecoecyathus* cf. *T. pusillus*, *Perisphinctes* cf. *P. lincki*, Choffat, *Lithoceras* aff. *stenoceras* Schmidt not Fontannes, *Katrolcerus* sp.?, *Calpionella alpina* Lorenz, *C. elliptica*, *C. unduloides*, *Nannoceras*, *N. steinmanni*?, *Textularia* sp., *Haplophragmoides*, and *Oligostegina* sp. The microfaunal assemblage indicates an Upper Tithonian age (Smout, unpub. data, 1953-59). At 'Iyadh one ammonite was found, determined as *Barriacella* sp., and it is of probable Tithonian age.

No Jurassic is known from Dhufar (R. W. Wetzel and D. M. Morton, unpub. data, 1948-50; Beydoun, 1960, 1964). Recent work in the area by the Dhufar Cities Service Petroleum Corp., however, indicates that elastics occurring below datable Early Cretaceous are of Jurassic age. Their age is based on spore and pollen determination and on the finding of *Coskinalinopsis primaceus* Henson (indicating a Liassic age) in a thin limestone in the elastics (J. M. Meier, written commun., 1961). These elastics suggest that only a part of the Jurassic remains in Dhufar, or else that only a part was deposited, Dhufar having been emergent during most of the period. The Jurassic elastics may be equivalent to part of the Kohlan Formation of the E.A.P.

REGIONAL CORRELATION OF THE JURASSIC

Plate 5 shows the correlation of the Jurassic formations of the area with those of neighboring countries.

The Kohlan Formation correlates with the Kohlan Series of Yemen (Lamare and others, 1930; Lamare, 1936) though Lamare's Kohlan is much more marly in its lower part. Originally (Lamare and others, 1930) this formation was given a Middle to Early (?) Jurassic age, but later (Lamare, 1936), on the basis of plant remains of a somewhat undiagnostic character found near the top of the succession and assigned to the Lias with reservation, it was assigned a Triassic or Liassic age and was correlated with the Adigrat Sandstone of the Ethiopi-Somali region.

Geukens (1960) described a succession of elastics occurring in various parts of Yemen between the basement peneplain and datable Upper Jurassic calcareous deposits and grading up into the base of this sequence. These deposits represents the Kohlan Formation, generally considered by him to be of Jurassic age.

The Adigrat Sandstone in former British Somaliland shows a gradational upper contact with the overlying Upper Jurassic limestone without any evidence of break and is taken to be Jurassic in age (Mason and Warden, 1956; Beydoun, 1964).

The Amran Series of Yemen (Lamare and others, 1930; Lamare, 1936; Geukens, 1960) is correlated only with the Shuqra Formation of the Amran Group of the E.A.P. This correlation is based on a similar facies and almost the same age range (Lamare and others, 1930; Lamare, 1936; Basse and others, 1955; Geukens, 1960; Wissmann and others, 1942).

Conformably overlying the Amran Series proper in various parts of Yemen are "transition" or "passage" beds (Wissmann and others, 1942; Basse and others, 1955; Geukens, 1960), variably including gypsum, clays, marls, and bituminous shales of Kimmeridgian age; they are more evaporitic east-northeast of Ṣan'ā' (Al Ghars, Al Harrah) but pinch out in places.

These transition beds of Yemen are therefore correlated with the Sabatayn and Madbi Formations of the E.A.P. The Ramlat as Sab'atayn basin appears to have extended westward from the E.A.P. and parts of W.A.P. into Yemen to include Ṣāfir, and to the vicinity of Ṣan'ā' (Basse and others, 1955; Wissmann and others, 1942; Geukens, 1960). Outside this rather restricted basin in the rest of Yemen, open-sea deposits similar to the Madbi Formation of the E.A.P. were being deposited—(shales, marls, limestones, and sandstones in near-shore areas) (Geukens, 1960). The Ṣāfir succession is very similar to that of the Ramlat as Sab'atayn, with the M'qah Member facies in the upper part; spore and pollen determinations from shale beds give a late Jurassic age (Delcourt, in Geukens, 1960).

In Yemen there are no beds equivalent to those of the Naifa Formation of the E.A.P. This is significant in

that it indicates that the south-to-north Naifa marine transgression which deposited limestone in the E.A.P. and the W.A.P. following Madbi and Sabatayn Formation deposition, did not reach Yemen. The zone of maximum subsidence during the late Jurassic, which was in Yemen in Amran Series (Shuqra Formation) time, shifted toward Hajarawit by Madbi and Sabatayn times.

Tentatively, E.A.P. (and W.A.P.) Kohlan Formation may be equivalent to the Marrat and Dhurma Formations of Saudi Arabia (Lower to Middle Jurassic) (Steineke and others, 1958), or even to the Minjur Formation. The Shuqra Formation is in part equivalent to the Tuwaiq Mountain Limestone and probably in part to the Hanifa and Jubaila (?) Formations. The Madbi and Sabatayn Formations are tentatively correlated with the Riyadh Group (Hith and Arab Formations). The Naifa Formation would then be equated with the Sulay Limestones, the age of which is a subject of controversy.

Southward from the Aden Protectorate, the Jurassic of former British Somaliland correlates well with that of the E.A.P. and W.A.P. but there is no evaporitic facies within the Jurassic in Somaliland.

ECONOMIC ASPECTS

No oil has so far been discovered in the E.A.P., but indications of the presence of hydrocarbons are found in the rocks of Jurassic age. These include bituminous occurrences associated with salt (Shabwa Member of Sabatayn Formation), bituminous shales (Layadim Member of Sabatayn Formation, and Madbi Formation), and oily shales and limestone (Naifa Formation). None of the occurrence are striking, but compared to other areas where Jurassic oil has been found (eastern Saudi Arabia, Qatar), conditions of source, reservoir, and caprock exist in the E.A.P. which should be favorable for some accumulation of oil.

Other Jurassic mineral occurrences consist of rock salt which is quarried from the various salt domes in the interior for local consumption and limited export within southwest Arabia.

One or two limited occurrences of iron in mineralization zones along local faults in Jurassic rocks have been found in the Wahidi State, but difficulty of access and limited extent make them noncommercial.

CRETACEOUS SYSTEM

The Cretaceous deposits of the E.A.P. vary in lithology, and thickness from west to east. Unconformities, disconformities, and pinchouts mark intra-Cretaceous movements, transgressions, and regressions or shallowing.

Cretaceous deposits are well exposed in the E.A.P. and occur along most of the length of the coastal belt, in the deeper gorges of the Southern Plateau, in the Wādi Hājramawt-Al Masilah basin, in the cliff faces of the western parts of the Southern and Northern Plateaus, in a few of the deep western gorges of the Northern Plateau, as well as over part of the Western Plains as hillocks.

It is in southwest Hājramawt that the succession is generally completely exposed. West of long 48°38' E. the Cretaceous rests unconformably on Jurassic, the contact being generally marked by a thin conglomerate; little or no angularity is observed. East of long 48°38' E. in the Al Mukallā area, the Cretaceous rests unconformably on peneplaned basement. From that locality eastward to Al Masilah the base of the Cretaceous sequence is not seen, but in Al Masilah and at Ra's Sharwayn, exposures go down to the Upper Jurassic, and evidence of unconformable contact is present (p. H22).

In view of the lithological variations of the Cretaceous as a whole between the eastern and western parts of the E.A.P., it has been divided into two equivalent lithostratigraphic groups, (a) the Tawilah Group for the Western (Hājramawt) Province, and (b) the Mahra Group for the Eastern (Al Mahrah) Province.

The two are equivalent in total age range, the Tawilah being dominantly a clastic sequence with some limestone and marl tongues in the east, whereas the Mahra Group is a dominantly limestone and marl facies with sandstone tongues increasing to the west. The groups interfinger, and certain persistent lithological units are common to both. In addition, each group presents some variations from west to east; some of the formations merge and some become thicker.

The groups and main formation divisions are given in the following table.

Western Province (Uşjramawt)		Eastern Province Al Mahrah	
Tawilah	Mukalla Formation	Mahra	Sharwain Formation
	Not present		Mukalla Formation
Group	Harshiyat Formation	Group	Fartaq Formation
	Qishn Formation		Harshiyat Formation
Unconformity		Qishn Formation	
Jurassic or basement		Disconformity	

TAWILAH GROUP

The name Tawilah Group is a readaptation of Lamare's "Taouilah Series" (Lamare and others, 1930;

Lamare, 1936) of Yemen, which comprises there a succession of continental sandstones overlying datable Upper Jurassic strata.

The group as exposed in Hājramawt is a shallow-water to lagoonal-marine sequence that changes character from west to east (see following table). Although it is dominantly of clastic composition, the appearance of limestone, marl, and shale tongues, particularly eastward, enables subdivision into more distinct formations in that direction. Thus, it is thinnest in the Al Mukallā area, (calculated, 500 m) thickening west and northwest and also eastward to the zone of deeper subsidence and facies of the Mahra Group.

W.A.P.-E.A.P. border	Jabal Bilūm area	Al Mukallā area	Age
Tawilah Group (clastics, no limestone tongues present)	Mukalla and Harshiyat Formations (Rays member still persistent)	Mukalla Formation Lush Member Mukalla Formation	Senonian (probably Campanian and Maestrichtian)
		Sufa Member Harshiyat Formation Rays Member Harshiyat Formation	Cenomanian, Turonian(?), and Albian
	Qishn Formation	Qishn Formation	Aptian and Berremian
Unconformity			
Jurassic or basement			

The age of the Tawilah Group is Cretaceous by virtue of its occurrence between datable Late Jurassic and datable Paleocene. On the faunal evidence present in the limestone and in some shale tongues, it is Berremian to Maestrichtian in age. This age most probably applies even to the westernmost part where no fauna has been found.

QISHN FORMATION

The Qishn Formation is the lowest formation of both the Tawilah and Mahra Groups. It varies laterally between the two provinces, being considerably thinner in the Western Province, with some clastics in its lower part.

The type section is at Ra's Sharwayn in Al Mahrah near Qishn (Eastern Province), where the formation consists primarily of limestone and some marl, and is more than 400 m thick. Westward into Hājramawt toward the shoreline, the upper thick-bedded limestone part with its characteristic fauna persists, although it is much thinner and is partly clastic.

The reference section for the Qishn of the Tawilah Group is at Jabal ar Rays near Al Mukallā. This sec-

tion is the most typical for the formation in that province where the succession is 32 m thick. It consists of a basal conglomeratic shelly sandstone with bands of oolitic fossiliferous limestone overlain by an interval of marl, commonly shaly, and bands of sandy limestone; this interval is capped by about 17 m of massive to well-bedded limestone, in some places rubbly and other places recrystallized, that contains *Orbitolina* cf. *O. discoidea* (Gras) Henson and *Choffatella decipiens* Schlum, which indicate a Barremian and Aptian age.

In the Al Mukallā area the formation rests unconformably on peneplaned igneous basement, but farther west it rests unconformably on Upper Jurassic, generally without evident angularity. The upper contact is with the Harshiyat Formation and is apparently conformable. Near the E.A.P.-W.A.P. border the Qishn has either pinched out or passed laterally completely into clastics. In the intervening area between Al Mukallā and the western border, the formation is locally absent in some areas (Jabal Shaqb, Wādi Raymah, some 6 km respectively south and southwest of Jabal Shabb) probably as a result of persistent local uplift into Aptian times.

At Jabal Ghubār (near Burūm) 63 m mainly of sandstone and gypsiferous marls and siltstone and some conglomeratic layers is capped by the fossiliferous limestone carrying *Orbitolinas*. In this upper limestone at the Ath Thil'ah as Sufā (Tilla Sufā) section near Al Mukallā (Little, 1925; R. W. Wetzel and D. M. Morton, unpub. data, 1948-50), in addition to the Foraminifera, *Heteraster oblongus* has also been found (Wetzel and Morton, unpub. data, 1948-50; K. Joysey, unpub. data, 1948-60). At Al Min'ān, the basal generally clastic part contains the charophyte *Clareator* sp., and at various other sections in the limestone part *Pernacululus inopinus* and *Cylindroporella* sp. have been found (E. K. Elliott, unpub. data, 1955-59). The base is invariably marked by a thick conglomerate or sandstone with some pebbles generally locally derived from the underlying Jurassic or basement; this marks the advent of the Cretaceous sea. In the Jabal Billūm section, however, the Jurassic Qishn contact is marked by a sandy dolomitic limestone overlain by some marly limestone containing *Noia atara* (Romer) and *Pholodonta* cf. *collumbi* Coquand (F. Gosling, unpub. data, 1956).

The Qishn may overlies various zones of Jurassic for very short lateral distances and illustrates the effect of terminal Jurassic movements followed by planation prior to the Cretaceous transgression.

HARSHIYAT FORMATION

The Harshiyat Formation is well exposed in most Cretaceous sections of Iḥdramawt and consists pre-

dominantly of a sequence of clastics, mainly sandstones with current bedding and conglomerate zones; interbedded marl, siltstone, and some shale form distinct intervals at various levels, and plant remains have been found in these. Present within this sequence of clastics are two well-defined limestone or dolomitic limestone intervals; the lower occurs within the lower sequence of clastics and forms the Rays Member, and the upper caps the upper sequence of clastics and forms the Sufā Member. Where these two limestone tongues persist, they are readily recognized, and the Sufā Member enables a boundary to be placed between the Harshiyat and the overlying and lithologically similar Mukallā Formation. However, some 50 km westward and south-westward from the Al Mukallā area, the Sufā Member pinches out and the Harshiyat and Mukallā Formations are no longer separable. The Rays Member persists for 20 or 30 km more to the west beyond this area before it too pinches out, and the whole succession of Harshiyat Formation becomes indistinguishable from the overlying Mukallā Formation. Eastward from Al Mukallā the Rays Member probably pinches out, but the Harshiyat Formation in its clastic facies continues into Al Mahrah, gradually changing character and passing laterally in its upper part into the limestone and marl facies forming the Fartaq Formation. In the Ra's Fartaq area, it all has passed laterally into this limestone and marl facies, and the entire Harshiyat is there replaced by the Fartaq Formation.

The formation is best developed in the Al Mukallā area where it also appears to be thickest, being 295-315 m thick. To the west of Al Mukallā, the thickness is in the order of 200 m but this may be partly due to local faulting out, though depositional thinning as a result of probable persistent local uplift into the Albian may have also taken place. Abrupt lateral variation within the clastics occurs, so lateral correlation of marl or shale intervals is not possible.

The faunal assemblage found in the Sufā Member shows that the upper part of the Harshiyat is of Cenomanian age; the lower part rests conformably on the Barremian and Aptian Qishn Formation, and is thus considered to be Albian in age. The base of the Sufā Member in one section (Ath Thil'ah as Sufā) is glauconitic and may mark a local disconformity.*

Rays Member.—The Rays Member consists of gray to brown, bedded to semimassive, coarsely recrystallized, partly dolomitic, ferruginous limestone that weathers reddish brown and attains a maximum measured thickness of 9 m in its type section at Jabal ar Rays near Al Mukallā. Owing to recrystallization, no

* There appears to be some relation between concentrations of glauconite and stratigraphic breaks, but opinions vary on this.

recognizable fauna has been preserved other than possible crinoid fragments. The Rays Member thins westward and pinches out some 80 or 90 km west of Al Mukallā. Southwest from Al Mukallā it becomes very thin and sandy. At Jabal Shaqb and in Wādi Raymah it almost directly overlies peneplaned basement, separated from the latter by a thin sandstone layer or a conglomerate. This suggests the persistence of local highs in these localities up to and including the earlier part of the period of deposition of the Harshiyat Formation. Occurrence of the Rays above the base of the Harshiyat is variable and probably was dependent on the influence of such local highs preceding or continuing into Harshiyat deposition. At Ath Thil'ah as Sufā (near Al Mukallā) there is no trace of the Rays Member and it may have either laterally passed into a marl sequence or been faulted out.

Sufia Member.—The Sufia Member is marine limestone tongue occurring at the top of a clastic sequence, and is gray, crystalline, in part fine grained and in part coarse grained, massive, and generally abundantly fossiliferous. Its maximum thickness of 16 m occurs at the Ath Thil'ah as Sufā section near Al Mukallā where it contains the following fauna (unpub. data from the following: R. G. S. Hudson, 1948-56, L. R. Cox, 1949-56, M. Chatton, 1948-59, and K. Joysey, 1948-60): *Eozogrya olisiponensis* Sharpe, *E. flabellata* Collignon, *Ctenocholetypus* cf. *C. larteti* Cotteau, *Choletypus larteti* Cotteau, and *Orbitolina* cf. *O. concava* (Lamark); this fauna indicates a Cenomanian age. The base at this section is slightly glauconitic. It thins and then tongues out westward, first becoming sandy and dolomitized in that direction. Eastward from Al Mukallā, it may persist and thicken into the Al Mahrah Province to form part of the Fartaq Formation.

MUKALLA FORMATION

The Mukalla Formation consists of a clastic sequence primarily of colored, friable, and current-bedded sandstone, with pebbly zones and subordinate marls and siltstones. At Ath Thil'ah as Sufā, a thin fossiliferous limestone bed capping a sequence of marls occurs with the clastics and forms the Lusb Member.

The formation is widespread in its occurrence in Ḥaḍramawt and can be seen wherever the Tertiary cover has been eroded. It persists eastward into Al Mahrah in much the same facies and also extends into Dhufar. In Ḥaḍramawt, it overlies the Harshiyat Formation apparently conformably. Where the Sufia Member of the Harshiyat is present, the division between the two formations is at the top of the Sufia; there is no indication of a break. Where the Sufia Member is absent, the Harshiyat and Mukalla Formations merge as one continuous sequence of clastics with-

out possible division; this applies especially to the westernmost part of Ḥaḍramawt. Thus, the age of the Mukalla Formation in Ḥaḍramawt has to be assumed. Fossils from the Lusb Member (which in itself has only been found in the Ath Thil'ah as Sufā section) indicate that the formation is partly Campanian in age. On the basis of correlation with Al Mahrah, the formation there is considered post Turonian, that is, Senonian.

The upper part of the formation is also a sequence of clastics and appears to be conformable with the overlying Paleocene formation. On faunal evidence, however, the upper contact is disconformable. In one section at the top, a small remnant of datable Maestrichtian in a clastic facies with thin carbonate beds has been found underlying datable Paleocene without visible field evidence of a break (Jabal Dubbah and Jabal Shabb); and in one other section, derived and reworked Maestrichtian fauna have been found in the basal meter or so of the Paleocene strata (Ra's Muwaysah) (p. H31).

The uppermost part of the Mukalla Formation in Ḥaḍramawt is therefore, in some sections, Maestrichtian in age. It would appear that the limestone Sharwain Formation of Maestrichtian age found in eastern Al Mahrah passes westward through a limestone-marl facies and then laterally into Ḥaḍramawt as clastics, datable only in a few localities and reduced in thickness to a mere tongue. These Maestrichtian clastics form a continuous sequence with the Mukalla Formation of Ḥaḍramawt, and most probably are either partly or completely eroded farther west in Ḥaḍramawt or have pinched out.

Apart from the fauna in the Lusb Member and the remnant of Maestrichtian fauna in the topmost part of the Mukalla in a few localities, the rest of the formation has so far proved unfossiliferous. The top is taken at the contact of the highest clastics (with or without thin bands of limestone or dolomite) and at the base of the papery shale (with or without thin bands of limestone) (p. H34) (M. Chatton, unpub. data, 1948-59). The shales and thin limestone commonly contain a good Paleocene faunal assemblage. If the shale is absent, the contact is taken at the base of the datable Paleocene limestone immediately overlying the Mukalla clastic sequence.

The Mukalla Formation in the Al Mukallā area is 165 m thick at Jabal ar Rays; it thickens westward at Jabal Shabb to 271 m. Westward from the latter area, it is not divisible from the underlying Harshiyat (p. H26). Exposures to the north do not permit accurate estimates of thickness, but it appears that some thickening occurs in that direction also.

Lusab Member.—The Lusab Member is a very local member found only at Ath Thil'ah as Sufiá (near Al Mukallá). It is approximately 50 m thick, the top 5 m consisting of nodular reddish-brown-weathering limestone containing *Liostrea thompsoni* Peron, *Gryphaea vesicularis*, *Penopea*, and *Hantkania* sp. (unpub. data from the following: Chatton, 1948-59; L. R. Cox, 1949-56; and R. G. S. Hudson, 1948-56). These indicate a Campanian (Senonian) age. The limestone is underlain by 45 m of yellow, green, and ochereous gypsiferous marls and obscure bands of marly limestone (R. W. Wetzel and D. M. Morton, unpub. data, 1948-50). To the west the limestone cap pinches out and the underlying marls probably pass into clastics and are not distinguishable.

MAHRA GROUP

The Mahra Group comprises the formations of Cretaceous age in a primarily limestone and marl facies exposed in Al Mahrah (Eastern) Province of the E.A.P.

The group varies in lithology from sandstone in the west to a predominantly carbonate succession in the east; it also thickens to the east. The age of the group is Barremian to Maestrichtian, based on comprehensive faunal evidence. The following table shows the facies.

Mahra Group (Barremian to Maestrichtian)

From west to east			Age
Al Masfih area	Ra's Sharwayn area	Ra's Fartak area	
Sharwayn Formation	Sharwayn Formation	Sharwayn Formation	Maestrichtian
Mukalla Formation	Mukalla Formation	Mukalla Formation	Senonian
Fartak Formation (Turonian(?) and Cenomanian)	Member Tubbay Member Dha Sobia Member	Absent	Turonian(?) and Cenomanian to Albian
Harshiyat Formation (Cenomanian(?) to Albian)	Unconformity	Fartak Formation	
Qishn Formation	Qishn Formation	Qishn Formation, part exposed	Aptian and Barremian
Unconformity	Disconformity	Not exposed	
	Jurassic		

QISHN FORMATION

The Qishn Formation has been examined in Al Mahrah at Ra's Sharwayn (type section) and Al Masfih where it is well exposed, and has been seen at Ra's Fartak where only 15 m of it is exposed (R. W. Wetzel and D. M. Morton, unpub. data, 1948-50; Beydoun, 1964).

At Ra's Sharwayn the formation is 411 m thick and consists almost entirely of limestone with marl zones

and bands, alternating in the upper half with rubbly marly limestone and some shale stringers. The limestone is partly shaly, partly oolitic, and partly shelly, and it locally contains chert nodules. The base of the whole succession is marked by some 5 m of brecciated limestone—taken as evidence of unconformity (M. Chatton, unpub. data, 1948-59; Beydoun, 1960)—resting on a sequence of limestone which though it is without diagnostic fossils, probably represents the uppermost part of the Jurassic (p. H22). The Qishn is fossiliferous, and contains *Choffatella decipiens* Schlumberger in its lower part down to the top of the basal brecciated limestone. *Orbitolina cf. Odiscoidea* (Gras) Henson occurs in the upper part together with *Diplopodia hermonensis* de Loriol, *Toxaster dieneri* de Loriol, *Coenholcystypus portontoneus*, and *Neithca cf. Nsirina* Conrad (unpub. data, from the following: Chatton, 1948-59; K. Joysey, 1948-60; and L. R. Cox, 1949-56). Some oysters and rare corals occur at various levels. On this faunal evidence, the age is Barremian and Aptian. In this typical section, the formation is overlain unconformably by the Mukalla Formation of Senonian age, the middle Cretaceous being entirely absent, most probably owing to local emergence at the end of the Aptian or during Albian time.

In Al Masfih, a succession of strata totaling 498 m is attributed by the author to the Qishn Formation; the basal 99 m contains nondiagnostic fauna and consists mainly of limestone and marly limestone, with several sandstone, marl, and shale zones in the lower part. The base of the interval is marked by a thin conglomerate and sandstone. This conglomerate overlies sandy Upper Jurassic beds (p. H22). (The advent of sandy limestone in the underlying beds is believed indicative of Late Jurassic shallowing and probable emergence.) The basal conglomerate would thus indicate the Jurassic-Cretaceous unconformity, and the start of the Cretaceous transgression as seen clearly in Hadramawt (p. H26).

The succession above the basal 99 m can be divided into 189 m of marly limestone and limestone with two main shale intervals, beneath 210 m of alternating shale and marl and marly limestone. The lower part contains the lowest indication of Barremian age with the lowest occurrence of *Choffatella decipiens* Schlumberger from the base, together with *Dictyoconus arabicus* and *Chelonicerus martini* (d'Orb.) higher up (Chatton, unpub. data, 1948-59; L. F. Spath, unpub. data, 1955-57). A 2-m-thick gypsum bed capping a shale interval occurs 76 m from the base. The upper part contains *Orbitolina cf. O. discoidea* (Gras) Henson and *Chelonicerus aff. cornuclianus* (Chatton, unpub. data, 1948-59; Spath, unpub. data, 1955-57); the base of this part is disturbed and this may mark a break between the Barremian and

Aptian. The top is overlain apparently conformably by the basal shale of the Harshiyat Formation.

HARSHIYAT FORMATION

The Harshiyat Formation in Al Mahrah is known only from the Al Masilah area, being absent to the east owing to erosion (Ra's Sharwayn) or facies change (Ra's Fartak). In a section near Tihayr, 196 m of colored basal shale, partly marly and with bands of marl, containing *Orbitolina* cf. *O. discoidea* (Gras) Henson and *Knemissera* cf. *K. attenuatum* Hyatt at the base, is succeeded by current-bedded colored sandstone, with marl and shale zones, that alternates with shale and shaly marl containing sandstone bands; fauna includes *Eoogyra* sp., *echinoids*, *Orbitolina* cf. *O. concava* (Lamarck), and *pelecypods* (R. W. Wetzel and D. M. Morton, unpub. data, 1948-50). On the basis of this faunal evidence, an Albian to probable Cenomanian age is indicated. The contact with the underlying Qishn is conformable and the lithology shows a regression phase. The overlying formation is the Fartaq Formation; the base of the Fartaq is here represented by the Cenomanian Dha Sohis Member, and the junction is apparently conformable.

A lateral passage of Harshiyat occurs from west to east, clastics as represented by the Sufia Member of the formation in Ijadramawt (Tawilah Group) gradually being replaced by a limestone and marl succession to the east into Al Mahrah. At Al Masilah this lateral passage is only half completed; at Ra's Fartak farther east the change is completed with the full development of the Fartaq Formation.

FARTAQ FORMATION

The Fartaq Formation overlies the Harshiyat in the western part of Al Mahrah (Al Masilah) and the Qishn in the eastern part (Ra's Fartak). It is mainly a limestone-marl lateral equivalent of the Harshiyat Formation of Ijadramawt, as illustrated by the following table.

Ijadramawt (Western Province)	Al Mahrah (Eastern Province)	
Al Mukallil area	Al Masilah	Ra's Fartak
Harshiyat Formation (Cenomanian to Albian)	Fartaq Formation (Probable Turonian and Cenomanian) Harshiyat Formation (Cenomanian and Albian)	Fartaq Formation (Probable Turonian to Albian)
Qishn Formation	Qishn Formation	Qishn Formation

The type section at Ra's Fartaq is 510 m thick (R. W. Wetzel and D. M. Morton, unpub. data, 1948-50; Beydoun, 1960, 1964). The succession starts with a basal 6 m of shale with marly limestone bands and contains the *Knemissera* aff. *K. attenuatum*-*K. compressum* group, *Toxaster dieneri* de Loriol, *Coenoholcypus portentosus* Cotteau, and *Trochodiadema libanotica* de Loriol (L. F. Spath, unpub. data, 1955-57; K. Joysey, unpub. data, 1948-60). Contact with the underlying Qishn is conformable and is based on the slight change of facies from the deeper water Qishn to the shallower water Fartaq (M. Chatton unpub. data, 1948-59); the change is not easily observable in the field. Above the basal shale is 184 m of partly marly crystalline limestone, with some bands of marl; oolitic and silty layers occur. This sequence is fossiliferous, containing *Coenoholcypus portentosus* Cotteau, *Diplopoda hermonensis* de Loriol, *Orthopsis* cf. *O. granularis* Cotteau, *Polyconites verneuili* Bayle, and *Orbitolina* cf. *O. discoidea* (Gras) Henson, passing upward into *Orbitolina* cf. *O. concava* (Lamarck) (Joysey, unpub. data, 1948-60; Chatton, unpub. data, 1948-59). The remainder of the succession, some 320 m thick, consists of two-thirds limestone and one-third marl in alternating intervals; the limestone contains marly bands and some shale streaks, and the marl contains marly limestone bands and is in part gypsiferous. The entire sequence is fossiliferous. *Prædvoolina cretacea* (d'Archiac) appears fairly low down and persists to the top (Chatton, unpub. data, 1948-59). Among other fauna present are the following: *Eoradiolites liratus* Conrad, *Neithea* cf. *N. subatanus* Blankenhorn, *Eoogyra flabellata* Goldfuss, *E. matheroviana*, *Coenoholcypus serialis* Deshayes, *C. cf. C. exicus* Cotteau, *C. ? larteti*, *Heterodiadema libyrum* (Desor), *Diplopoda variolara* Brongniart, *Hemaster journalis* Desor, and *H. cubicus* (unpub. data from the following: R. G. S. Hudson, 1948-56; Joysey, 1948-60; and Chatton, 1948-59).

The faunal assemblage of the whole formation gives it an age range of Albian and Cenomanian to probable Turonian. The formation is apparently conformably overlain by the Mukalla Formation, but a disconformable contact is possible.

In the Al Masilah area the formation is much thinner in occurrence and is equivalent only to the upper part of the Fartaq Formation of Ra's Fartak (p. II_m). The total thickness here is about 209 m, divisible into three distinct units which have been given member status as they are not recognizable individually farther east. Together these make up the Fartaq Formation of Al Masilah. Their total age range on the basis of faunal evidence is Cenomanian to probable Turonian. From

base to top, they are the Dha Sohis, Tihayr, and Maqrat Members.

Dha Sohis Member.—The Dha Sohis Member is some 40-48 m thick and consists of a lower marly, rubbly limestone, and thin shale, a middle shale unit, rather gypsiferous and capped by glauconitic marl, and an upper marly limestone unit with chert nodules at the top (R. W. Wetzel and D. M. Morton, unpub. data, 1948-50). A Cenomanian age is based on the presence of *Orbitolina cf. concava* (Lanarck), pelecypods, corals, and echinoids, including *Toxaster dieneri* de Loriol (Joysey, unpub. data, 1948-60). The member varies laterally, and near Maqrat in the Al Masilah area it is composed entirely of a rather massive limestone of reef facies, containing rudists as well as *O. cf. O. concava* and other forms. The Dha Sohis overlies the Harshiyat Formation apparently conformably though the contact is somewhat obscured. It is believed to be equivalent to the Sufia Member of the Harshiyat Formation of Hajarawt (Tawilah Group).

Tihayr Member.—The Tihayr Member is about 70 m thick and consists primarily of a series of green and purple shales, in part gypsiferous, and containing some bands of marly limestone and an interval of colored sandstone near the top (Wetzel and Morton, unpub. data, 1948-50). *Eozoglya flabellata* Goldfuss, *Heterodiadema tibeyum*, *Coenocleptus serialis*, and *Echinocorys* sp. (Hudson, unpub. data, 1948-56; Joysey, unpub. data, 1948-60) indicate a Cenomanian to possible Turonian age. It overlies the Dha Sohis Member conformably.

Maqrat Member.—The Maqrat Member conformably overlies the Tihayr Member and is apparently conformably overlain by the Mukalla Formation. It is about 100 m thick and consists of a limestone sequence; near the base this passes into dolomitic limestone, and in the upper part it becomes coarse, containing thin streaks of marl (Wetzel and Morton, unpub. data, 1948-50). Foraminifera and other fossils are present but are generally recrystallized. *Pyrina cf. P. petracoriniensis* (Chatton, unpub. data, 1948-59) occurs at the base, and other fauna include *Præaeolonia* sp., rudists, gastropods, and pelecypods. The age range of Cenomanian and probable Turonian is indicated from the above faunal assemblage.

MUKALLA FORMATION

The Mukalla Formation is common to both the Tawilah and Mahra Groups of Hajarawt and Al Mahrah respectively; it is the only formation that persists in the two provinces without any real change in lithological character. The formation has already been adequately described (p. H27-H28) and it is sufficient

here to merely outline some facts about its character in the Eastern (Al Mahrah) Province as part of the Mahra Group.

At Ra's Fartak the formation is 142 m thick, and apparently conformably overlies the Fartaq Formation there, though the contact is somewhat obscure. It consists of sandstone with bands of shale, silty marl, and siltstone, and sparse thin bands of fossiliferous limestone (R. W. Wetzel and D. M. Morton, unpub. data, 1948-50). At Ra's Sharwayn, it is only 96 m thick and unconformably overlies the Qishn Formation. It consists of a sequence of sandstone and some shale bands. At Al Masilah, it is 112 m thick and again consists of sandstone with some marly layers and siltstone, and apparently conformably overlies the Maqrat Member of the Fartaq Formation (Wetzel and Morton, unpub. data, 1948-50; Beydoun, 1960). In all three section areas it is conformably overlain by the Maestrichtian Sharwayn Formation.

The age of the Mukalla Formation is taken to be Senonian, though no diagnostic fauna has been found in it. However, by virtue of its occurrence between Cenomanian to probable Turonian, and Maestrichtian, a general Senonian age is indicated.

SHARWAYN FORMATION

The Sharwayn Formation is the top formation of the Mahra Group and has been examined in three localities in Al Mahrah (R. W. Wetzel and D. M. Morton, unpub. data, 1948-50). It shows a passage westward from a limestone sequence, through a marl and limestone sequence, to a marl sequence. The type section is at Ra's Sharwayn.

In the east at Ra's Fartak a 48-m sequence of a slightly marly crystalline limestone with rudists in the lower part overlies the Mukalla Formation conformably and represents the Sharwayn Formation of this area (Wetzel and Morton, unpub. data, 1948-50; M. Chatton, unpub. data, 1948-59; Beydoun, 1960, 1964). It is conformably overlain by a thick sequence of bedded to massive saccharoidal limestones of dateable Paleocene age which belong to the Umm er Radluma Formation. The Maestrichtian transgression in the Ra's Fartak area was continued in the Paleocene transgression without a noticeable regressional phase as found to the west.

At Ra's Sharwayn 66 m of Sharwayn Formation is present. The sequence begins with a 26-m-thick succession of marl containing harder calcareous concretions and capped by shale; *Lepidorbitoides minor* (Schlumberger) and *Loftusia persica* Brady occur throughout (Chatton, unpub. data, 1948-59). Then comes a 13.5-m-thick succession of marl, calcareous and hard in the basal part, and containing *Lepidorbitoides socialis*

(Leymerie) and *Loftusia morgani* Douville (Chatton, unpub. data, 1948-59). The upper 26.5 m consists of limestone, marly at the base and crystalline upward, and containing *Omphalocyclus macroporus* (Lamarck), *loftusius*, and rudists (Chatton, unpub. data, 1948-59). The faunal assemblage indicates a Maestrichtian age. The succession is overlain by gray-white marl which is glauconitic at the base and was considered by Chatton to belong to the base of the Umm er Radhuma Formation.

At Al Masilah the formation is represented by 30 m of marl with harder calcareous bands, shaly to gypsiferous in places, overlain by 5 m of shelly limestone. *Loftusius* are common throughout, and the contact with the underlying Mukalla Formation is apparently conformable and somewhat gradational upward from sandstone through sandy marl to the marl of the Sharwain. The contact with the overlying Umm er Radhuma is also apparently conformable. However, on consideration of the westward thinning in the Sharwain Formation in Al Mahrah and its passage into thin clastics in Hjadramawt, the contact is probably disconformable, marking a slight break between the Maestrichtian and Paleocene transgressions.

In Hjadramawt near Ash Shilr the clastics of the Mukalla Formation are overlain by approximately 4 m of fine clastics and a thin limestone bed containing *Omphalocyclus macroporus*, *Glyptomella* sp. and *Gyrogonia*, directly overlain by datable Paleocene of the Umm er Radhuma (Chatton, unpub. data, 1948-59). Farther west at Jabal Shabb, west of Al Mukalla, the unfossiliferous clastics of the Mukalla Formation are capped by 5 m of additional clastics, mainly siltstone and shale with some marl, which contain *Haplophragmoides* sp. 4. These beds are overlain by 7 m of unfossiliferous argillaceous and dolomitic limestone and shale, which in turn is overlain by 3 m of dolomite, shale, clay, and glauconitic sandstone that contains *Omphalocyclus macroporus* (Lamarck), *Fissoclephidium operculiferum* (Smout), *Loftusia* sp., and rare *Rotalia* cf. *R. trochidiformis* (Lamarck). Datable Paleocene occurs 2 m above (Chatton, unpub. data, 1948-59). Thus, in this section, datable Maestrichtian in a clastic facies with carbonate bands totals some 15 m. At Ra's Muwaysah, a few kilometers to the south, reworked Maestrichtian fauna has been found at the contact of the Mukalla and the Umm er Radhuma (Paleocene) Formations, associated with the Paleocene fauna of the latter. In none of the many other Cretaceous-Paleocene contact sections examined in Hjadramawt has any Maestrichtian fauna been found. The Sharwain Formation in Hjadramawt is thus represented by a much restricted and reduced clastic sequence present only in the eastern part of coastal Hjadramawt,

and also is partly eroded; it was either never deposited or completely eroded away farther to the west.

DHUFAR

As a result of unpublished work by R. W. Wetzel and D. M. Morton in 1948-50 and visits to some Dhufar sections by the author (by courtesy of the Dhofar Cities Service Petroleum Corp.), a composite stratigraphic column of Cretaceous sedimentary rocks has been reconstructed from the scattered sections examined. From this it is seen that progressively younger Cretaceous rocks rest directly and unconformably on pre-Cretaceous beds from west to east, the progression indicating that a land surface existed which was first submerged in the west (Early Cretaceous times) and only later submerged in the east (Late Cretaceous times). The pre-Cretaceous land surface in the west at Al Hawtah and 'Ayn Sarit exposes peneplaned and folded Lower Paleozoic (?) and basement sedimentary rocks (?) (p. H12). Resting on this surface are mainly clastic Lower Cretaceous rocks (part Jurassic at the base). Near Mirbat to the east, Murbat Formation clastics of probable Ordovician age (p. H13) discordantly underlie Lower (?) but most probably middle Cretaceous beds. The Murbat Formation wedges out eastward, and at Ra's Naws in the east, facing the Kuria Muria Islands, the old surface consists of peneplaned (granite) basement overlain by Upper Cretaceous sedimentary rocks.

The facies of Cretaceous sedimentary rocks in Dhufar appears similar to that of the Al Masilah area of the Al Mahrah Province (E.A.P.), and the Cretaceous formations of Dhufar could thus be included in the Mahra Group. A Qishn Formation at the base is recognized, consisting of a marly sequence followed by limestone containing *Choffatella decipiens* and *Orbitolina* cf. *O. discoidea* (Barremian-Aptian). A Harshiyat Formation is also recognized. This rests on Murbat Formation in the Mirbat area, and consists of a lower clastic sequence of shale overlain by sandstone and terminating with marl containing *Orbitolina* cf. *O. concava* (Albian-Cenomanian). A reduced Fartaq Formation is recognized overlying the Harshiyat type marl and consisting of limestone with *Pracaelveolina cretacea* in its upper part (Cenomanian-probable Turonian). In some sections (mainly in the western part) the Fartaq Formation equivalent is overlain by limestone of Late Cretaceous age containing *Pseudotextularia* sp.; the limestone appears to be conformable over the Fartaq equivalent, though in some places an unconformity is reported and the limestone is reduced in thickness and contains Maestrichtian fossils. This limestone appears to represent an entirely carbonate Upper Cretaceous facies, unknown in the E.A.P. and apparently restricted to the western part of Dhufar. Finally, in the east (facing

west of the Kuria Muria Islands) a thin limestone tongue containing Late Cretaceous (Senonian) fauna rests on a very thin Murbat (or basement) Formation (†) and is overlain conformably by a sequence of clastics. The clastics with their basal limestone tongue are the Mukalla Formation equivalent for Dhufar. Over these are Tertiary beds.

REGIONAL CORRELATION OF THE CRETACEOUS

Plate 5 shows the main correlations of Cretaceous units with neighboring countries.

In Socotra Island (administratively part of the E.A.P.) only part of the Cretaceous is present. Original geological work on Socotra and Samhah (Semha) Island was done by Kossmat (1907). More recently, the present author made a geological reconnaissance on Socotra Island (1953-59); micropaleontological examination of the author's samples was done by A. H. Smout (unpub. data, 1953-59). As a result, a revision of the Cretaceous stratigraphic stages as indicated by Kossmat has been made and shows that only Albian and Turonian strata were deposited on Socotra and that these belong to the Al Masilah area facies.

A basal clastic formation thinning from east to west consists of sandstone and marl and limestone beds that contain *Radiolites*, *Caprinidae*, *Modiola*, *Ostrea*, and *Orbitolina discoidea* var. *discoidea* (Smout, unpub. data, 1953-59); all occur mainly in the upper part. This is regarded as a Harshiyat Formation equivalent some 100 m thick, and it rests on peneplaned igneous basement (mainly granite). Its age would be Albian and Cenomanian. Overlying this formation conformably is a sequence of limestones, rudistic in the lower part, marly with interbedded marl and some sandstone at the base of the middle, and chalky in the upper part. Fauna includes *Radiolites*, sparse *Hippurites*, *Caprina*, *Orbitolina discoidea* var. *discoidea*, *Ostrea flabellata*, *Exogyra decussata* Goldfuss, *Orthopsis miliaris*, *O. perlata* Noetl., *Pseudodiadema marticensis*, *Pholadomya vignesii*, *Terebratula semiglobosa* var. *albensis*, *Orbitolina* cf. *O. lenticularis*, *Pseudocyclammina*, *Textularia*, and *Præaëcolina* sp. (Smout, unpub. data, 1953-59; Kossmat, 1907), all of Cenomanian and Turonian affinities. This sequence represents the Fartaq Formation equivalent of the Mahra Group. The top of the succession is overlain unconformably, though without any visible break in the field, by datable Paleocene limestones.

In Somalia (Hunt and others, 1956; Macfadyen, 1933; Mason and Warden, 1956; Somaliland Oil Exploration Co., Ltd., 1954; Beydoun, 1964) the Cretaceous shows a change of facies from east to west as it does in the E.A.P. from Al Mahrah to Hajarawt, the main area of former British Somaliland being covered by

clastics (equal to "Nubian Sandstone") similar to those of the Tawilah Group of Hajarawt, but a special shale-clay facies within the sandstone sequence (Nubian) occurs locally (for example, Shabel and Durato beds) (Macfadyen, 1933).

In Yemen, Lamare (Lamare and others, 1930; Lamare, 1936) described a continental series of sandstone with conglomerate from the San'a' region which he called the Taouilah Series. He assigned it a Cretaceous age, probably Cenomanian in its upper part. During the latter part of the Cretaceous, volcanic activity on a large scale took place in Yemen and volcanics rather than sediments were deposited during that time (trap series) (Lamare and others, 1930; Lamare, 1936; Geukens, 1960).

Geukens (1960) subdivided Lamare's Taouilah Series sandstone into a lower "Nubian" facies (continental to lagoonal in origin) which he called Taouilah Series and for which he retained the Cretaceous age; the upper series he called the Medj-Zir Series, this being a neritic succession containing marine fauna, on the basis of which a Paleocene or Eocene age is indicated. The Taouilah Series (Geukens, 1960) correlates with the Tawilah Group of the E.A.P. and W.A.P.

Correlation with Saudi Arabia is much more difficult, but on a total age range the Tawilah and Mahra Groups of the E.A.P. probably correspond to the Biyadh, Wasia, and Aruma Formations of Saudi Arabia (Steineke and others, 1958), though breaks between these formations are represented by continued sedimentation in the E.A.P. The Yamama and Buwaib Formations of Saudi Arabia are not represented in the E.A.P. and the Hauterivian (and at least part of the Berriasian) are missing at the Jurassic-Cretaceous unconformity in the E.A.P.

ECONOMIC ASPECTS

Little (1925) reported on the lignite occurrences in the Al Mukalla area. These are toward the top of the Mukalla Formation and, though fairly persistent and of good quality, are not of commercial value owing to the extreme difficulty of exploiting them. Little also reported on some limited occurrences of bauxite, which are also noncommercial.

Cretaceous sandstones of the Tawilah Group offer some good reservoirs for hydrocarbon accumulations that migrate from older rocks, but caprock is somewhat limited and deep erosion exposes much of these beds. No hydrocarbon indications are known from beds of the Tawilah Group. The formations of the Mahra Group in the carbonate facies may offer suitable conditions for the generation and accumulation of hydrocarbons, but it is not known how far inland this facies extends away from the broken coastal part.

The Cretaceous Tawilah Group formations generally are good aquifers, being reservoirs for all runoff in the rugged and faulted coastal part, particularly where the overlying Paleocene is badly broken. In the unfaulted north where the Cretaceous clastics are reached in drilling, and particularly in the west, regional water accumulations of good potability are found. This is particularly true in the Al' Abr-Zamakh-Minwakh area and in the northern plains.

CENOZOIC ERA TERTIARY SYSTEM

Tertiary deposits are widespread in south Arabia and cover the greater part of the E.A.P. and Dhufar. Where erosion and faulting has cut through them to expose older rocks in the E.A.P., particularly in the south, the Tertiary beds have often been preserved in down-faulted blocks together with the older rocks.

The Tertiary Period commenced with the strongly transgressive Paleocene, so by the end of the Paleocene, mainly carbonate deposits were spread over the greater part of south Arabia (E.A.P., Dhufar, Oman), the Persian Gulf region, the Horn of Africa, and the island of Socotra. In most of the W.A.P. and Yemen, this period was primarily marked by large-scale volcanic activity. Marine Eocene deposits were then laid down over the Paleocene in the entire region (except Yemen and W.A.P.), to be followed by emergence in the upper Eocene.

During the Oligocene and Miocene in the E.A.P. and Dhufar, marine sediments were deposited over much smaller areas, mainly in coastal embayments in which they are still preserved.

The rest of the Tertiary Period involved no further major marine sedimentation; post-Miocene deposits consist of coastal beach terraces and reefs, river terraces, eolian and fluvial deposits, and renewal of volcanic activity in the E.A.P., and W.A.P., which persisted into Recent times.

The Tertiary deposits of the E.A.P., and to a large extent of Dhufar, can be divided into three stages. The first stage brought about major marine deposition of a group of sediments that were primarily carbonate, but with evaporitic and clastic phases which are placed together under one group—the Hadramut Group, divisible into several formations. The second stage is one of lesser marine deposition of a varied nature that occurred in embayments into an existing coastline, established as a result of general uplift. These heterogeneous deposits have been grouped together as the Shihir Group, which, however, has not been divided into separate formations. In Dhufar, Oligocene and Miocene deposits, mainly chalky limestones, were also laid down near the present coast. During the third

stage no noteworthy marine transgression occurred, and such marine sediments as were deposited are the results of oscillations in sea level over an established coastline. Accompanying eolian, fluvial, and lacustrine deposition occurred over a land surface which was much the same as it is at the present time. Toward the close of the Tertiary Period, volcanic activity commenced in the coastal districts of the E.A.P. (and W.A.P.), and persisted till Recent times.

HADRAMUT GROUP

The Hadramut Group includes all sedimentary strata of Tertiary age from the Paleocene to the middle Eocene, namely all deposits laid down after the end of the Maestrichtian (which generally involved a phase of regression and planation in the region (p. H30-H31) and before the upper Eocene emergence. The deposits are marine, in the main carbonate deposits, but they include shale, marl, and some evaporitic deposits of Eocene age.

The following table gives the formations of the Hadramut Group. The appropriate ages given for each formation are those for the E.A.P. type and reference sections, but some transgressing of stages by formations occurs within and outside the E.A.P.

Emergence		Upper Eocene
Hadramut Group	Habshiya Formation	Middle Eocene (Lutetian)
	Rus Formation	Lower Eocene
	Jeza' Formation	
	Umm er Radhuma Formation Disconformity	Paleocene Planation
Cretaceous		

The Hadramut Group varies in overall thickness. Accurate estimates are not possible in most places because of the postmiddle Eocene unconformity and the general lack of exposure of the basal formations in an area of generally flat-lying rocks.

From measurements of individual formations in various parts of the territory, however, the thickest sections occur in the area of Al Masilah and its tributaries in Al Mahrah, where all formations are well developed and preserved. This region marks the flanks and axial areas of a broad structural depression marked by the Hadramawt-Al Jiz' syncline. Thick but incomplete sections of the group crop out in the Ra's Fartak area in south Al Mahrah. The area appears to be

more basinal. Thinning of the group appears to take place westward and northward from the coastal areas and from the synclinal area of the Haqdamawt-Al Jiz' basin. This thinning and its relation to tectonic development are discussed later (p. H41).

UMM ER RADHUMA FORMATION

The Umm er Radhuma Formation is strongly transgressive in facies; it forms the basis of the Tertiary tableland of the E.A.P. and Dhufar and crops out in cliff faces wherever this tableland is deeply dissected or faulted.

The name Umm er Radhuma was first applied in Saudi Arabia where the type section for the formation occurs (Steineke and others, 1958). The age in Saudi Arabia is considered to be Paleocene and lower Eocene, and the thickness at the type section is about 230 m.

In the E.A.P. the Umm er Radhuma Formation consists mainly of limestone of Paleocene age, easily distinguishable from the overlying lower Eocene shale-limestone succession of the Jaza' Formation. However, in some parts of the territory, namely in southeast Al Mahrah (for example, Ra's Fartak and the Damqawt area) and in Dhufar, limestone sedimentation was continuous from Paleocene through early Eocene time, making it increasingly difficult in most places to divide the two formations; where they are indivisible the Umm er Radhuma includes Paleocene-lower Eocene.

The type reference section for the formation in the E.A.P. is at Say'un in Wādi Haqdamawt where the formation was measured and sampled by R. W. Wetzel and D. M. Morton (unpub. data, 1948-50) and later by Beydoun and others (unpub. data, 1953-59). This section, which is typical of the formation in the E.A.P., shows the following characteristics from base to top: A basal dolomite some 1.5 to 2 m in thickness is overlain by (1) a 4-m basal interval consisting of (a) 2 m of ochre and gray papery shale containing scarce *Lockhartia* sp. and ostracodes followed by (b) 2 m of fine-grained nodular limestone containing the same fauna and also algae, (2) 9 m of marly limestones that are nodular weathering and exfoliating, become massive upward, and contain *Lockhartia haimi* Davies, *L. diversa* Smout, and *Daviesina khatiyahi* Smout (M. Chatton, unpub. data, 1948-59; A. H. Smout, unpub. data, 1953-59), and (3) a 43-m sequence of massive-weathering dark-brown and dark-gray limestone, fine to coarse grained, in parts marly, nodular in the upper part, and commonly containing calcite veins and chert vugs. Unit 3 is distinctive and in some sections it is very dolomitic and recrystallized, but regardless of this, it is invariably distinguished by its massiveness and dark color; it forms a distinctive cliff in the lower part of the

formation. Fauna in this unit includes those already mentioned under unit 2, together with *Taberina daviesi* Henson, *Kathina seleeri* Smout, *Valvulina triangularis* d'Orbigny, *Dictyoconus* sp., and shell debris. The rest of the type section consists of massive white and gray limestone, with dolomitic, chalky, calcarenitic, and shelly zones. It is nodular weathering and locally cavernous owing to scaly disintegration and exfoliation; scattered chert nodules occur. In the coastal districts the cavernous weathering is striking, accentuated by wind erosion and local slumping. The whole of this sequence is generally rich in microfauna which include: *Lockhartia conditi* (Nuttall), *L. tipperi* (Davies), *Sakesaria* cf. *S. cotti* Davies, *Nonionella* cf. *N. jacksonensis* Cushman, *Globorotalia velascoensis* (Cushman), *Rotalia trochidiformis* (Lamarck), *Operculina sindensis* Davies, *O. patalensis* Davies, *O. salua* Davies, *Assilina dandotia* Davies, *Aranikoti* Nuttall, *Nummulites wadani* Davies, *N. thalicus* Davies, *N. globulus* Leymerie var. *indicus* Davies, *Furcoporella diplopora* Pia, and *Ovulites* sp. (unpub. data from the following: Chatton, 1948-59; Smout, 1953-59; and G. F. Elliott, 1955-59). On the basis of this faunal assemblage a Paleocene age is indicated.

In Haqdamawt, the Umm er Radhuma Formation overlies Upper Cretaceous Mukalla Formation clastics. Although contact appears to be conformable in the field, it has proved on faunal consideration to be disconformable (p. H31).

The actual position of the contact between Paleocene Umm er Radhuma Formation and Upper Cretaceous Mukalla Formation in Haqdamawt has been open to controversy. Some observers (Chatton, unpub. data, 1948-59) prefer to include in the Cretaceous the basal dolomite below the 4-m interval described in unit 1, and take it to be representative of Maestrichtian. They place the contact at the base of the overlying papery shales (base of unit 1), which often contain Paleocene Foraminifera. In some sections this shale is much thicker and may include thin limestone bands, or, as in the 'Amāqin section, it may have sandstone layers above it, whereas in the other sections it is absent and limestone rests directly on clastics or on a thin dolomite. In such localities the base of the limestone is taken as the base of the Paleocene transgression and thus as the base of the Umm er Radhuma Formation. As this view seems to be supported in some places by faunal evidence, it is adopted here, although in the field differentiation between papery shale zones occurring at the top of the Mukalla Formation and those at the base of the Umm er Radhuma Formation is not easy. Neither is it easy to distinguish between thin dolomites and recrystallized limestones occurring in some sections in several bands

over the critical contact zone. The papery shales at the top of the Mukalla Formation have been described by Chatton (unpub. data, 1948-59) from thin-section examination as deposits indicating a lagoonal to semi-epaporitic phase that marked a regressional period at the end of the Maestrichtian. On the other hand, the papery shales in the base of the Umm er Radhuma appear, on the basis of thin sections, to be transgressive deposits.

Variation in the thickness of the formation in the E.A.P. is associated with the growth and development of the biaxial Hjadramawt arch and its Hjadramawt-Al Jiz' syncline (pl. 6). The most marked thinning takes place, however, toward the line of the north axis of the biaxial arch, with the probable absence of basal Paleocene north of this line and the pinching out of the lower massive unit (described as unit 3) toward this line. All this suggests that the north axis may have been active as a barrier during early Paleocene time and later submerged in the middle Paleocene. (*Laesina wichmanni* (Smout, unpub. data, 1953-59) is found at the base of the succession north of the axis.)

The Umm er Radhuma Formation is regarded as partly equivalent in age to the trap series of Yemen (Wissmann and others, 1942). In Hjadramawt, it thins toward a Paleocene shoreline presumably somewhere in the W.A.P., and it thickens eastward into Al Mahrah; in the Ra's Fartak-Damqawt sector of eastern Al Mahrah and in Dhufar, the limestone facies continues upward well into lower Eocene, this part laterally replacing the Jeza' Formation.

Ra's Fartak is a good example of the upward extension of the limestone facies but is also a locality where a carbonate Jeza' Formation may still be recognized. Wetzel and Morton (unpub. data, 1948-50) measured 318 m of cliff-forming limestones and some dolomite cropping out massively, overlain by 177 m of limestone containing dolomite and scattered chert nodules and bands. These are overlain by marls of the Habshiya Formation of Lutetian age. Thus, between the top of the elastics of the Mukalla Formation and the marls of the Habshiya Formation is 493 m of continuous carbonate deposits. The sequence is on the whole fossiliferous, enabling age and formation divisions to be made within it. The basal 43 m represents the Sharwain Formation (p. H30). This unit differs from the overlying 154 m of massive yellow-white rather saccharoidal sequence of limestones that weathers brown and contains *Lockhartia condidi* Nuttal, *Daviensina khatiyahi* Smout, *Rotalia* sp., *Quinqueloculina* sp., and *Dietyoconus* sp. (Chatton, unpub. data, 1948-59). This assemblage gives the sequence a Paleocene age, and

the succession represents the lower part of the Umm er Radhuma.

The rest of the massive cliff face, 116 m thick, is made up of much the same sequence of limestone but includes some dolomite and a basal marl bed in which the lowest occurrence of *Alveoline ovoidea* d'Orbigny is recorded together with *Sakessaria cotteri*. *Rotalia* sp. "A" occurs higher up with *Alveolina ovoidea* (Chatton, unpub. data, 1948-59; Wetzel and Morton, unpub. data, 1948-50). The assemblage indicates an early Eocene age but the succession still belongs to the Umm er Radhuma Formation. The top 177 m crops out on a gentler slope, the lower 86 m consisting of massive limestone and dolomitic limestone, with scattered chert nodules and *Alveolina ovoidea* d'Orbigny and *A. globosa* Leynnerie (Chatton, unpub. data, 1948-59); the topmost 103 m consists of thin-bedded partly chalky limestone with thin shale partings and chert bands. The age of this 177-m sequence is early Eocene; the lower massive 86 m belong to the Umm er Radhuma Formation, whereas the upper thin-bedded 103 m represents the Jeza' Formation in a limestone facies (p. H36) (Beydoun, 1960, 1964). Thus, at Ra's Fartak is a continuous carbonate sequence ranging in age from Maestrichtian at the base through Paleocene to early Eocene.

JEZA' FORMATION

The Jeza' Formation is typically formed in western Al Mahrah and Hjadramawt; there it overlies, and is easily distinguishable from, the Umm er Radhuma Formation and forms a typical mesalike landscape on top of the Umm er Radhuma tableland. It is not present in easternmost Al Mahrah or Dhufar.

The type section for the formation is in the Al Masilah basin in western Al Mahrah. There in the Wādi Hībūn area, 133 m of Jeza' Formation consists of alternations of papery yellow and pink shale, some marl and thin bands of limestone, chalky to crystalline limestone (in places silicified and with bands of chert), and some bands of gypsum near the top. Fauna is abundant and includes dwarf echinoids, lamellibranchs, ostracodes, and the following Foraminifera: *Rotalia trochidiformis* Lamarek, *Lockhartia* cf. *L. cotteri* Davies and Pinfold, *Sakessaria tipperi* Davies, *S.* cf. *S. cotteri* Davies and Pinfold, *L. tipperi* Davies, *L.* aff. *L. hamei* Davies, *Nummulites* aff. *N. globulus* Leymar, var. *indicus* Davies, *Dietyoconus* aff. *D. indicus* Davies, and *Opeculina* aff. *O. subaala* Davies (M. Chatton, unpub. data, 1948-50). The faunal assemblage indicates an early Eocene age.

The Jeza' overlies the Umm er Radhuma Formation conformably. In the southeastern sections of Al Mahrah, it is generally distinguished from the Umm er Rad-

huma by the appearance of marls (Ra's Sharwayn and Ra's ad Darjah), but where no marl is present (Ra's Fartak), but the thinner bedding and partly chalky facies of its limestone distinguish it from the Umm er Radhuma. At Damqawt and in Dhufar, however, these characteristics are lost, and there the Umm er Radhuma Formation includes the Jeza' Formation equivalent. The Jeza' is overlain in the type area and in western Al Mahrah and Hjadramawt by the Rus Formation and the contact is conformable, in many sections also being gradational. Transition beds (included in the Rus for mapping) are present between the Jeza' and the Rus in several sections in north Hjadramawt. In the Ra's Sharwayn-Ra's Fartak sector and somewhat northward from there, the Rus Formation is absent, and the Jeza' Formation (or equivalent) is overlain by the Habshiya Formation.

Although at the type section the Jeza' is of early Eocene age, the lower part of the formation may range in age to Paleocene. At Ra's Sharwayn Paleocene fossils are present in the basal few meters, and in northwest Hjadramawt (Zamakh area) these forms persist for some way up.

Variations in thickness of the Jeza' Formation occur. The thickest sequence is probably in the southeast and in the Hjadramawt-Al Jiz' synclinal area, with slight thinning westward and northward.

RUS FORMATION

The type locality for the Rus Formation is in Saudi Arabia (Steineke and others, 1958). In the E.A.P. the type reference section is in the Al Masilah basin in western Al Mahrah. There in Wadi Ijibun a thickness of 138 m consists of bedded to massive gypsum and some bands of interbedded limestone that are chalky to gypsiferous or silicified in the lower part and gypsiferous chalk in the upper part; some marl and porous limestone bands as well as chert nodules also occur in this part. There are no fossils (R. W. Wetzel and D. M. Morton, unpub. data, 1948-50). The Rus Formation rests conformably on the Jeza' Formation, with slight gradation indicated by thin bands of gypsum in the top of the Jeza'; it is overlain conformably and also somewhat gradationally by the Habshiya Formation, gradation appearing with the advent of chalky beds in the top of the Rus.

The age of the formation, by virtue of its occurrence over datable lower Eocene Jeza' Formation and under middle Eocene Habshiya Formation, is considered to be early Eocene. The formation may, however, be somewhat diachronous over long distances (for example, it probably is in part Middle(?) Eocene in Dhufar).

The Rus Formation is developed over most of the E.A.P. except in the extreme southeast corner of Al Mahrah in the Ra's Fartak-Ra's Sharwayn area, where it was either never deposited or not developed as an evaporitic formation. This area probably remained well supplied by refreshing currents so that evaporitic conditions did not arise.

The Rus Formation appears best developed in the Wadi al Jiz' basin and in the eastern part of the Wadi Hjadramawt basin where it is thickest. It is widespread over most of the Northern Plateau, but is preserved only in a local synclinal depression although in thick occurrences) on the eastern part of the Southern Plateau in Hjadramawt and over most of the extension of the depression in Al Mahrah, as well as in the tectonic river valley of the Wadi Hajar basin and a part of Wadi Mayfa'ah. It crops out over a large area of northern Dhufar.

Over most of the territory the formation contains thick beds of gypsum or anhydrite with associated thin dolomite bands and chert, and the upper and lower parts commonly are transitional. The upper contact, however, is abrupt in many sections in Hjadramawt, though it is still apparently conformable, suggesting a possible discontinuity between lower Eocene evaporites and the middle Eocene transgression. In north Hjadramawt and north Al Mahrah, however, apparent local and lateral variations to chalky deposits, many gypsiferous, and to gypsiferous marls, are common, particularly in north Al Mahrah where the dwarf echinoid *Sismondia polymorpha* Duncan and Sladen (K. Joysey, unpub. data, 1948-60) of probable early Eocene age has been found in chalky deposits with embedded calcite geodes. This local and lateral variation from evaporites is consistent with behavior elsewhere—for example, Saudi Arabia, Qatar (Steineke and others, 1958; Sugden, 1966)—and is probably due to water replenishment or the influence of currents. In other parts of the northern territory local replacement of the gypsum by solution breccia occurs and is generally accompanied by formation of collapse structures. Near the edges of the depositional basin the Rus thins and then pinches out or passes laterally into lower and middle Eocene deposits of the Jeza' and Habshiya Formations.

HABSHIYA FORMATION

The type section for the Habshiya Formation is in the western part of the Wadi al Jiz' basin where 224 m was measured (R. W. Wetzel and D. M. Morton, unpub. data, 1948-50). The succession consists of gray-green, yellow, and pink papery shale and yellow chalky and gypsiferous marl alternating with limestone and chalky

and dolomitic limestones; the shale and marl are dominant in the lower half. The whole succession is rich in fauna, including *Nummulites gischensis* (Forskel), *N. discorbinus* (Schloth) var. *major* Rozlos, *N. staminis* Nuttall, *N. aff. N. radiat* Davies, *N. sub-stacicus* Douville, *Dictyonoides kohaticus* Davies, *Assilina spira* (de Roissy), *Alveolina elliptica* var. *nuttalli* Davies, *Heterocella fragilis* (Defrance), *Thal-moporella* sp., and "*Gymnocodium nummuliticum*" Pfender (unpub. data from the following: M. Chatton, 1948-59; A. H. Smout, 1953-59; G. F. Elliott, 1955-59; K. Joysey, 1948-60). Abundant dwarf echinoids are associated with the microfauna, represented by *Echinocyamus nummuliticus* Duncan and Sladen, *E. subcaudatus* (Desmoulin), and *Simondia marginalis* (Desmoulin) (Joysey, unpub. data, 1948-60); these have been collected from the formation in other localities in the territory. Other echinoid fauna is common in the upper part at the type section and at other sections in the E.A.P. (such as Jabal Habbshiyah) and include *Echinolampus ovalis* B. de St. Vincent, *E. discoides* d'Archiac, *E. fraasi* de Loriol, *Schizaster africanus* de Loriol, *S. vicinialis* Agassiz and Desor, *Duspatangus formosus* de Loriol, *Opisaster derasmoi* Checchia-Rispoli, *O. digonus* d'Archiac, *Linthis somaliensis* Currie, and *Migliorinia migiurtina* Checchia-Rispoli (Joysey, unpub. data, 1948-60). This faunal assemblage gives a Lutetian (middle Eocene) age to the formation.

The formation is thick in the northern part of the territory, forming the capping rocks of the crestal area of the North Haddramawt arch from about long. 49°30' E. and eastward into Dhufar; the belt progressively broadens eastward from its western extremity at Jabal Habbshiyah. In the Wādi al Jiz' basin and up onto that part of the Southern Plateau to the south, the formation is again present, but it does not occur westward on the Southern Plateau and is only preserved in a few localities in southwest Haddramawt.

The formation overlies the Rus Formation in most of the E.A.P. Its contact with the Rus is conformable, though in several localities there is a clean-cut change from evaporites to shales and marls, indicating a possible time break in those localities between evaporitic deposits and Lutetian transgressive deposits. In many sections, however, the Rus becomes transitional at the top (p. 1336). In southeastern Al Mahrah, where no Rus is present, the Habbshiyah overlies the Jeza' or Umm er Radhuma Formation.

Over most of the E.A.P., the Habbshiyah Formation has much the same lithology as in the type area, but in southwest Haddramawt where it is present in the Wādi Hajar basin in small outcrops—Qur'ān Raḡmah (Ruḡ-

mah)—the advent of sand in sandy limestone and of siltstone and silty shale within the formation indicates nearness to a shoreline probably somewhere nearer to the W.A.P. border area. At Damqawt, near the Dhufar border on the coast, a thick sequence of *Alveolina*-bearing limestone (Wetzel and Morton, unpub. data, 1948-50) probably comprises almost wholly Habbshiyah Formation equivalent, and in Dhufar the Habbshiyah is equivalent to two formations of middle Eocene age, namely the Andhur and Qara Formations; the Qara was partly referred to by Fox (1947) to be late Eocene. The Andhur Formation consists of alternating limestones, dolomites, and marls with abundant Lutetian fauna; it is overlain by variable limestone of the Qara Formation which also contains a rich Lutetian fauna (Wetzel and Morton, unpub. data, 1948-50). The Andhur may, however, actually pass in part into the Qara, the two being probably partly synchronous.

SHIHR GROUP

The Shihr Group comprises a transgressive sequence of sedimentary strata of varied lithology occurring in scattered generally scree-covered outcrops that form part of a depositional sequence laid down in coastal embayments after the emergence of the E.A.P. territory in the terminal Eocene. Into these embayments and morphotectonic depressions marine ingressions made their way, while at the same time a recently risen land-mass was undergoing erosion and rivers were transporting a variety of material into this sea.

Outcrops are discontinuous, of varying thickness, and covered by scree and raised beaches, and deposits are heterogeneous; moreover the work done on these deposits was insufficient for dividing them into formations.

The strata making up the group consist of conglomerate, sandstone, marl, gypsum, reef limestone, chalky limestone, shale, and some dolomitic limestone, occurring singly or in combinations of several of the types mentioned. This variation in lithology was dependent on the proximity to emerged land surfaces undergoing erosion, on proximity to lagoons and river mouths, on presence in restricted or semirestricted basins, on contact with open shallow sea and favorable currents, or on distance from the coast and quiet-water conditions. Despite this diversity of lithology it is apparent from the study of the various sections that the strata belong to one group embracing one major episode. This group is mainly of clastics, the polygenetic conglomerate and sandstone laterally passing into marls or shales away from the source of material and toward the more open sea; at times the open sea became restricted, or lagoonal conditions resulted in the deposition of evaporites. Where oscillations occurred, evaporites are interbedded

with clastics. Reef developments occurred from early in this phase of sedimentation wherever conditions were suitable, and continued to develop with intermittent subsidence and reworking (for examples, Buwaysh near Al Mukallā) until probably late in the Miocene.

In two sections described here a good fauna has been found, but in most places the succession is barren. The reefs have a good fauna of Foraminifera, corals, algae, and some echinoids, and some of the chalky limestones have yielded good foraminiferal assemblages. Oligocene and Miocene macrofauna have been found, but the foraminiferal assemblage is Aquitanian and Burdigalian in age. The Aquitanian is regarded by some paleontologists as being lowest Miocene overlain by the Burdigalian; others regard it as uppermost Oligocene and regard it as uppermost Oligocene and regard the Burdigalian as lowest Miocene. Gignoux (1950) pointed out that on the basis of mammalian fauna the Aquitanian must be regarded as uppermost Oligocene. In this account the Aquitanian is tentatively considered as transitional between the Oligocene and Miocene. The presence at the Buwaysh section of some Oligocene (s.l.) echinoids, *Schizaster vicalis* Agassiz and Desor (upper Eocene and lower Oligocene range, R. G. S. Hudson, unpub. data, 1948-56), in association with Aquitanian-Burdigalian Foraminifera confirms at least an Oligocene age for the lower part, and Miocene (Burdigalian) for the rest, though a younger age including Pliocene for some of the conglomerates is probable.

At Jabal Dabjab some 25 km west of Ash Shilr, a succession of interbedded coarse clastics and gypsum with bands of marl is capped by a chalky limestone containing a good microfaunal assemblage which includes the following: *Lepidocyclina* cf. *L. vaughani* Cushman, *L. sumatrensis* (Brady), *L. tournoueri* Lemoine and R. Duville, *L. yurnaguensis* Cushman, *Miogypsina* sp., *Operculinoides tournoueri* (de la Harpe), *Operculina complanata* Defrance, *O. complanata* Defrance var. *heterostegina* Silvest., *Amphistegina* cf. *A. nissi*, *Gypsina globulus* (Reuss), *G. vesicularis* (Parker and Jones), *Globigerina bulloides* d'Orbigny, *Eponides* sp., *Cyclodiscus eidae*, *Nephrolepidina sumatrensis*, *N. marginata* (M. Chatton, unpub. data, 1948-59; A. H. Smout, unpub. data 1953-59) and the algae *Lithothamnium* in a top dolomitized limestone planed down to form a terrace. The age range of this fauna places the beds in the upper Aquitanian and Burdigalian. At Buwaysh, east of Al Mukallā, clastics are apparently overlain by foraminiferal and coral limestone with alternating thin sand and sandy marl. Fauna includes *Schizaster vicalis* Agassiz and Desor in the lower part of the limestone, *Operculina complanata* Defrance, *Eulipidina ephippioides* (Jones and Chapman) S. S.,

Nephrolepidina marginata (Michelotti), *Miogypsina* sp., *M. cf. M. globularis*, *Globigerina bulloides* d'Orbigny, *Pararotalia* cf. *P. mexicana* (Nuttall), *Amphistegina* cf. *A. lessoni* d'Orbigny, *Cibicides* sp., *Operculinoides* sp., *Astrocoenia* sp., *Chlamys pallium*, *Leptomusca* sp., *Favia* spp. and algae (Hudson, unpub. data, 1948-56; Smout, unpub. data, 1953-59). The fauna is Oligocene (s.l.) to Aquitanian and Burdigalian.

At Jabal Mathanah in the Wādī al Ghabar area some 50 km west-southwest of Al Mukallā, the succession is mainly conglomerate with interbedded sandstone and some gypsiferous sandy marl in the lower part. North of Ra's Fartak in Al Mahrah, some 150 m of Shihir Group beds is preserved and consists of a series of orange marls with gypsum, conglomerate, and thin beds of dolomitic limestones.

In the Karif Shawrah volcano near Bi'r 'Ali, some limestone ejecta belong to the Shihir Group and contain fauna as follows: *Taberina Malabarica* (Carter), *Meandropsina anahensis* Henson, *Borealis melo* (Fichtel and Moll), echinoid debris, corals, and gastropods (Smout, unpub. data 1953-59). The foraminiferal assemblage indicates a Burdigalian age.

The Shihir Group can rest on any of the older formations depending on morphology and erosion at the time of deposition. Its conglomerates contain pebbles and cobbles of all older rocks exposed near the areas of deposition. It has been seen to rest on Habbshiya Formation, on Jeza' Formation, on Rus Formation, on Tawilah Group, and on basement. Its contact with the sedimentary strata below is unconformable, but not everywhere with angularity. It is not overlain by any younger formations but various levels of it have been planed and covered with raised beach or river-terrace material.

In Dhufar a marine Oligocene sequence ranging in age from early to late Oligocene is thickly developed in the coastal area near Salālah and farther east at Ra's ash Shuwaymyyah on the Oman border. The facies is one of chalk and chalky limestone; the basal part contains shale and marl with chalky limestone, and *Nummulites fichteli* Michelotti-intermedius d'Archiac is common; the rest of the succession contains *Lepidocyclina* and *Eulipidina* fauna and echinoids (Beydoun, 1964; Chatton, unpub. data, 1948-59). Miocene reef-type limestone and associated shale with *Ostrea* and *Pecten* overlie the Oligocene chalk and chalky limestone. Some observers in Dhufar postulate an unconformity between these and the Oligocene, and others include them as part of an Oligocene and Miocene cycle, while separating an overlying younger series of virtually horizontal limestone conglomerates as belonging to the Pliocene and Pleistocene (Dhofar Cities Service

geologists, written commun., 1959). Although the limestone conglomerates are similar to those of the Shihr Group conglomerates of the E.A.P., their horizontal nature as compared to the tilted and disturbed nature of the Shihr Group conglomerates makes correlation between them dubious. Thus the Dhufar Oligocene (Miocene?) deposits differ from those of the E.A.P., except probably in parts of western Dhufar.

POST-MIOCENE DEPOSITS

Post-Miocene deposits fall largely outside the scope of this account and have been adequately described by Little (1925), Caton-Thompson (1938), Caton-Thompson and Gardner (1939), Wissmann (Wissmann, 1932; Wissmann and others, 1942), R. W. Wetzel and D. M. Morton (unpub. data, 1948-50), and others. However, a brief summary of these observations plus others made by the present work is not out of place in completing the stratigraphic description of the E.A.P. This summary also applies in general to Dhufar.

Raised beaches.—The following levels of raised beaches in the Al Mukallā area appear to be persistent terraces: 6-10, 25, 50, 60, and 75-80 m. In addition, a 100-120-m terrace is suspected. The 6-10-m terrace is the most recent and occurs in scattered localities along the coast, commonly as a wave-cut platform with abundant loose corals. The 25-, 50-, 60-, and 75-80-m terraces affected Shihr Group deposits by planing their tops, the last planing also occurring near Burūm and at Ra's al Mukallā, Umm er Radhuma Formation. The 100-120-m terrace and a suspected terrace at 150 m are indicated on Al Mukallā hill where Miocene(?) and younger corals are found plastered on Umm er Radhuma Formation on the side of the hill.

Caton-Thompson (1938) found paleolithic implements associated with 32- and 14-m terraces. Wetzel and Morton (unpub. data, 1948-50) observed "fossil" dunes backing the shoreline of a 15-m terrace.

Some fauna has been collected from the lower terraces at various localities and determined as follows: *Lophatrinata* (Lamarck), *Chlamys* cf. *C. porphyrea* Chemnitz, *Conus* cf. *C. litteratus* Linne, *Cypraea* cf. *C. carnea* Linne, *Alteocyona cucullata* (Lamarck), *Platygira lamellina*, *Stylopora pistillata*, *Fungia* aff. *F. pleistocenia*, *F. aff. F. zuffardiac*, *Favia* sp., *Cyphastrea* sp., *Goniastrea* sp., *Stylophora* sp., *Platyggyra* sp., *Monastrea* sp., *Montipora* sp., *Acropora* sp., *Solenastrea* sp., *Oulophyllia* sp., and *Leptoria* sp. (F. Gosling, unpub. data, 1956; R. G. S. Hudson, unpub. data, 1948-56). The above fauna is "usually considered to be Pleistocene, but faunally cannot be distinguished from Pliocene or Recent forms," according to Hudson.

River terraces and lacustrine deposits.—A number of river-terrace levels can generally be seen above the

present-day drainage levels of the bigger wadyān and overlying various older rocks from the basement upward. In lower Wādī Ifajr at least three such levels are seen, one being about 150 m above present wādī level; similar levels are found in Wādī al Ghabar and elsewhere, and are marked by coarse conglomerate with finer layers. These terraces reflect regional oscillations.

Wetzel and Morton (unpub. data, 1948-50) noted the widespread occurrence of a 30-35 m terrace in the E.A.P. Eolian deposits and silt in Wādī Hāgramawt and Al Masilah are embôitê in this terrace and are known to overlie gravels in some areas.

Lacustrine deposits are associated with river terraces in the middle Wādī Ifajr basin between Šidārah and Jawl Bā Hāyah (Jawl Bā Hawah). These deposits consist of sandy chalky marl and limestone, with *Chara* stems and gastropods, horizontally or subhorizontally bedded and laterally passing eastward into, and interfingering with, thick limestone conglomerates at Al Qa'imah village near Jawl Bā Hāyah. The age is probably Pliocene. Other lacustrine deposits occur in the north.

Gravel plains and alluvium deposits.—The formation of gravel plains already described (p. H4-H5) is due to action of both water and wind, and the plain surfaces may have been initiated in a pluvial period or periods in Pliocene or Pleistocene times. River silt is present in many localities now marked by hardly more than very flat broad drainage and within the sand-dune tracts of the territory.

Alluvial deposits, other than river terraces already discussed, include coarse gravel, sand, and silt in drainage channels, and conglomerates formed in wadyān beds by recementation of pebbles due to arid desiccation.

Eolian deposits.—Loess and fluviocolian deposits are fairly extensive, particularly in the Wādī Hāgramawt basin; they also occur in smaller wadyān of the plateaus and the coast. Three species of loess snails have been found (Wissmann and others, 1942) in these deposits; two of the species are widely distributed.

Terraces formed by these deposits are invariably cut by subsequent drainage and often exposed to their base where they are seen to rest on older river terraces. They mark a pronounced dry phase of Tyrrhenian(?) age, followed by rejuvenation of drainage. Sand dunes have already been discussed earlier (p. H4-H5).

Young eruptions.—Wissman (Wissmann, 1932; Wissmann and others, 1942), Lamare (Lamare and others, 1930; Lamare, 1936), and others have described and discussed the young eruptive rocks of southwest Arabia in detail. The present account briefly mentions these rocks as observed in the E.A.P. They form part of the Aden Volcanic Series.

The westernmost area of eruptive activity in the E.A.P. is in the Balhaf-Bi'r 'Ali region where several craters, including many cinder cones, occur, and the region is covered by volcanic deposits including basalt flows, tuff, and ash. The fresh tuff cone of Karif Shawrân near Bi'r 'Ali is a crater lake; the volcano was an explosive one that brought up a variety of older sedimentary rocks and an assortment of igneous rocks including granite and dunite. The main activity was restricted to the coastal strip and the neighboring part of the sea (close to the zone of strongest (?) faulting). Some activity took place inland, and basaltic flows associated with fissuring occur in limited outcrops in the Wâdi Hajr basin, piercing through Eocene sedimentary rocks, and on the side of Jabal Shabb piercing through Cretaceous. No further trace of eruptive activity is seen until the Qusay'r-Say-hût area in the east, where flows and cones occur along the coast and variable extents of lava flows pierce through Tertiary sedimentary rocks along fault or fissure lines on the plateau and in Al Masilah. No other evidence of volcanism is known from anywhere else in the E.A.P., and there is none in Dhufar.

These volcanics form part of a Pliocene, Pleistocene, and Recent phase of eruptions which occurred in the Gulf of Aden-Red Sea region. Volcanic activity in southwest Arabia commenced as early as the Late Cretaceous in Yemen (Lamare and others, 1930; Lamare, 1936) and parts of the W.A.P., and in Paleocene and Eocene times in most parts of the W.A.P. This activity continued intermittently in southwest Arabia until Recent times. The E.A.P. activity belongs to the later phase.

Wetzel and Morton (unpub. data, 1948-50) reported the thickness of flows in the Qusay'r-Say-hût strip to be from 10 to 60 m. In Al Masilah they recognized two flows; the older is embôitè in Pliocene conglomerate (generally overlies the 30-35 m terrace) and the younger covers the 12-16 m terrace in the wadiân. The recognition of two phases agrees with Wissman, Rathjens, and Kossmat (1942), who reported a first phase ascribed to the late Pliocene and a second phase of younger Pleistocene age.

REGIONAL CORRELATIONS OF THE TERTIARY

The main correlations of E.A.P. formations with neighboring areas are shown on plate 5.

The Eocene sedimentary rocks of the E.A.P. were originally referred to as Oligocene and Miocene (Little, 1925; Wissmann, 1932; Wissmann and others, 1942) but their very rich faunal assemblage shows them to be early and middle Eocene (p. H135-H136).

In former British Somaliland, the Auradu Limestone, Allahkajid Series, Gypsum-Anhydrite Series, and Kar-

kar Series are the counterparts of the Umm er Radhuma, Jezza, Rus, and Habshiya Formations of the E.A.P. both in lithology and in approximately the age range of each formation (Macfadyen, 1933; Hunt and others, 1956; Somaliland Oil Exploration Co., Ltd., 1954); a Paleocene age for at least part of the Auradu has been proved. The lower Daban Series of Somaliland appears to be a near-shoreline equivalent of the Karkar Series and reflects similar near-shore conditions as seen in the Habshiya Formation in Hadramawt near Jizwil (Qurun Hagmah) (p. H37). Strata equivalent to the Shihir Group are found in the middle and upper Daban Series and the Dubar Series. The Daban Series is middle Eocene to Miocene in age, without a break between the lower and middle Daban, and the latter is in part late Eocene in age (Macfadyen, 1933). This age would indicate that, for at least part of the Daban basin, subsidence and sedimentation were probably continuous from the middle Eocene to at least the Oligocene, and thus suggests a late Eocene initiation of the Gulf of Aden (p. H43). The presence of upper Eocene is not known elsewhere in the general area of the Gulf of Aden and south Arabia except in the Al Buraymi district. Somaliland Oil Exploration Co., Ltd. (1954), on the other hand, considered the middle Daban as Oligocene transgressive on middle Eocene Daban.

In Socotra (Beydoun, unpub. data, 1953-59) the Umm er Radhuma Formation has much the same facies as occurs in the Ra's Fartak to Damgawt area of Al Mahrah (and in Dhufar), and ranges in age from Paleocene to early Eocene (A. H. Smout, unpub. data, 1953-59). There are no Rus or Habshiya Formation equivalents, a break having occurred between lower Eocene and Oligocene. A succession of marine chalky limestone and marl with chert and flint, and containing abundant microfauna, can be found preserved in structural depressions (Beydoun, unpub. data, 1953-59). Fauna collected includes the following: *Operculina complanta* (Defrance) var. *granulosa* Leymerie, *Globigerina bulloides* d'Orbigny, *G. cf. G. sacculifera* Brady, *Lepidocyclina dilatata* (Michelotti), *L. tounoueri* Lemoine and R. Douville, *Archæaia cf. A. aduncus* (Fichtel and Moll), *Gypsina globularia* (Reuss), *Nannulites germanicus* (Bornemann), *Haplophragmium alingeri* Thomas, and *Austrotrillina* sp. (Smout, unpub. data, 1953-59). This assemblage indicates an Oligocene age. The facies indicates deeper open-sea conditions, with Socotra (and Dhufar) occupying an easterly and more basinward position in the path of the transgressing sea. The Oligocene deposits lie discontinuously on Umm er Radhuma Formation but without evident unconformity in the field. No deposits of the Shihir Group have been seen (Beydoun, 1964).

In Qatar (Sugden, 1966), eastern Saudi Arabia (Steineke and others, 1958), and the Trucial Coast (M. Chatton, unpub. data, 1948-59), the Umm er Radhuma, Rus, and Dammam Formations are the equivalents of the Hadhramut Group of the E.A.P. Facies in the Umm er Radhuma there is similar to that of the Umm er Radhuma of eastern Al Mahrah, but variations occur in the facies of the Rus and Dammam Formations compared with their equivalent Rus and Habshiya Formations of the E.A.P.

In the Oman desert (Morton, 1959), the Umm er Radhuma Formation occurs in the same manner as it does in most of the E.A.P., but the lower Eocene Jeza' and Rus equivalents consist of chalky marl and limestone, gypsiferous shale, dolomite, and dolomitic marl. The middle Eocene is most variable, being a massive nummulitic limestone facies in the north and yellow marl and rubbly limestone facies to the south (Morton, 1959), similar to the Habshiya Formation of the E.A.P.

A thick sequence of marine Oligocene, consisting of limestones and chalky limestones, occurs with a break between it and the Miocene. The Miocene consists of a lower part of limestone, chalk, and marl, and an upper part, largely detrital and evaporitic, which is correlated with the lower Fars of Qatar and the Trucial Coast (Morton, 1959).

In Yemen the Tertiary period was characterized by considerable volcanic activity but calcareous fine sands were deposited locally by a limited Paleocene-Eocene transgression (Geukens, 1960). In the W.A.P. volcanic activity predominated and Paleocene and Eocene deposits like those of the E.A.P. are confined to the easternmost part.

ECONOMIC ASPECTS

Lime preparation from burning Umm er Radhuma limestone is a small-scale local industry. If cheap fuels for the kilns can be found, this industry could be developed for export outside the E.A.P. The kilns are wood fired, but wood, being generally scarce, has to be collected from increasingly greater distances. The wood is also required for charcoal manufacturing, another small-scale local industry.

Gypsum-anhydrite of the Rus Formation occurs in large quantities, particularly in the north, but no exploitation of this product has been undertaken, one reason being difficulty of working because of distance from the sea. World demand is met from other sources where conditions of working are easier.

Celestite has been found in bands more than half an inch thick within the Jeza' Formation on the Southern Plateau. No survey to assess the extent and importance of these bands has been made, but from the amount seen

an assessment survey is probably justified and may prove promising.

Tertiary ground water is regional in the northern part of the E.A.P. and Dhufar (north flank of the North Hajramawt arch). Rus, Jeza', and Umm er Radhuma water has been found in good quantities in northern E.A.P. by drilling to an apparently regional water table. Similar conditions have been met in Dhufar. Salt contents are variable, but the water is generally potable. Umm er Radhuma water in these areas is generally under pressure and flows to the surface with varying ease depending on the hydrostatic head; on the whole, it is sulfurous but reasonably potable when allowed to stand.

In the more mountainous parts of the territory, springs occur at the base of the Umm er Radhuma or within the younger formations overlying impervious layers.

STRUCTURE

The E.A.P. and Dhufar are in the southern part of Arabia bordering the Gulf of Aden and the Arabian Sea. To the west are the W.A.P. and Yemen, both of which lie in the southwest corner of Arabia where the Red Sea, Gulf of Aden, and Ethiopian rift valleys meet in the region of what has been called the Afar triangle.

The E.A.P. and Dhufar thus fall outside the Afar triangle and the E.A.P. is bordered only by the Gulf of Aden rift. The area belongs to what has recently been referred to as the Hajramawt Plateau structural province (Aramco geologists), a description which, however, oversimplifies the structure.

The dominating topographical and structural feature of the area (E.A.P. and Dhufar) is the very gentle Hajramawt arch (s.l.) that spans the whole territory. It has two subparallel culminations in the North and South Hajramawt arches, separated by a broad gentle syncline. The structure is expressed in the morphology which developed mainly in the Tertiary.

The Tertiary structure is therefore described and discussed first, with an interpretation of the structural development. The next and final section gives a summary of structural history from the basement to the Tertiary as it is understood from the work so far carried out, and some comparison with the Somali side of the Gulf of Aden is given.

TERTIARY AND RECENT STRUCTURE

No local folding or faulting movements are known to have occurred during the early (Paleocene) stage of the Tertiary subsidence in the E.A.P., but in Paleocene and middle Eocene times the first indications are obtained in the stratigraphy (p. II35-II38) of the progressive development of the biaxial Hajramawt arch. This feature

attained its present form approximately at the end of the Eocene, though faulting in the later Tertiary gave it its final collapsed south flanks (pl. 6).

The main arch, roughly equivalent to Wissmann's "Südarabische Randschwelle" (Wissmann and others, 1942) (south Arabian marginal swell), has an intervening gentle syncline dividing it into the North and South Hadramawt arches respectively, together forming the highlands of the E.A.P. The axes of the two arches and the intervening Hadramawt-Al Jiz' syncline trend west-southwest in Hadramawt, gradually swinging from west to east in Al Mahrah.

The North arch extends eastward into Dhufar through the Al Qamar and Al Qarā' ranges; in the west it flattens out and is lost in the plain east of the Yemen border. The length is some 600 km or more. The axial zone is expressed by Eocene strata and marked by the highest ground of the Northern Plateau, which also approximately defines the watershed. The flanks dip very gently to the north and south, the overall dip being about 1°, though steeper dips exist locally. The axis pitches in the Mirbāt area of Dhufar where the feature is cut off by coastal faulting, but the Kuria Muria Islands may mark an extension of its basement core.

The median synclinal area is at present followed roughly by the lines of Wādī Hadramawt-Wādī al Jiz', the axis being slightly south of the Wādī Hadramawt line (p. H6). The syncline pitches eastward into the structural depression of Al Qamar Bay; westward it flattens out and is lost in the Shabwah area. Flank dips are very gentle, averaging about 1°.

The South arch has an observed length of some 350 km. In the east it plunges in the Ra's Sharwayn area where it is intersected by the coast; in the west a zone of faults trending west-northwest cuts across its axial line and its structural identity is obscured toward the W.A.P. border. Its northern flank is very gentle with dips of about 1°; but unlike the south flank of the North arch, the south flank of the South arch has collapsed as a result of subsequent large-scale faulting, doubtless associated with rifting in the Gulf of Aden. Owing to this faulting the arch is now bounded to the south along most of its course by a broken scarp rather than by a south-dipping flank, but the original flank is clearly seen in its eastern profiles in spite of step faulting.

Origin of the arch through warping (as distinct from faulting) is further indicated in evidence of its progressive development in the early Tertiary, when the facies and thickness distribution of contemporaneous sedimentary rocks were affected by it. Thus in any given profile in the eastern part, thick sections of Paleocene-Eocene strata are found on the two flanks of the South arch. These conditions suggest that the Gulf of Aden

region also developed as a structural depression during the Paleocene transgression while the beginning of a very gentle uplift was proceeding over the axial zone of the South arch.

Uplift of the North arch was probably a little more pronounced. Thickness measurements and studies in the western region of the North arch suggest that during the early part of the Paleocene transgression, the North arch was somewhat active, forming a northerly temporary or submerged barrier in the Paleocene sea along which thinning and pinching out or facies change of the lower unit of the Umm er Radhuma Formation occurred. Soon after, however, probably in the middle Paleocene, the sea overcame this and spread over the whole north (p. H34).

In the early Eocene, thickness variations again reflect progressive development of the Hadramawt arch (s.l.), and the maximum development of evaporites (Rus Formation) occurred in the intervening gentle synclinal trough of the Hadramawt-Al Jiz' line, again with greater thicknesses in the east than in the west. The evaporites are absent in the Ra's Sharwayn-Ra's Fartak coastal area, presumably owing to the pitch of the axis toward open-sea conditions.

During the middle Eocene, the Habshiya Formation of southwest Hadramawt thinned and became sandy toward a shoreline at about long 48°30' E. (p. H37), suggesting that geanticlinal uplift with an eastward pitch was continuing.

Progressive development of the Hadramawt arch (s.l.) as a geanticlinal warping led to final emergence in the upper Eocene; geophysical surveys indicate that the north flank continues to dip continuously under Tertiary cover toward the Rub' al Khālī in Saudi Arabia.

This interpretation of the Hadramawt Plateau structure differs from that of Wissman, Rathjens, and Kossmat (1942), who ascribed the steeper south dip to flexuring and associated normal faulting at depth. Normal faults passing, with decrease of throw, into flexures are frequently observed in rift zones, but none have been observed passing into flexures of the scale of the Hadramawt arch. The visible south flank of the simpler eastern part of the arch is broken largely by normal strike faults, but the strata in most blocks dip south toward the downthrown side, indicating that a south-dipping flank existed before the faulting (Wissman and others, 1942) (pl. 6). In the more complicated western sector where there are intersecting fault systems, the south flank is no longer recognizable as such.

It might be assumed that the whole flexure developed through draping of sedimentary strata over a basement stepped down toward the Gulf of Aden rift by numerous small normal faults. However, such normal fault-

ing would imply a tensional lengthening of the crust (in horizontal projection) to which a draped sedimentary cover would have to adapt itself by actual stretching to a degree which seems hardly credible, especially in massive limestones under little load. There seems no reason to suppose that the assumed buried faulting failed to rupture this cover, whereas later faults have done so. Moreover, basement rocks where exposed along the south flank do not show any step faults that diminish upwards into the sedimentary cover.

The linear continuity of the North and South Hadramawt arches over very long distances is opposed to origins either in normal faulting or in uplift due to expanding magma at depth (for example, Somaliland Oil Exploration Co., Ltd., 1954) which would probably produce shapeless bulges. For these reasons F. R. S. Henson (unpub. data, 1954-60) regarded the compound Hadramawt arch as a *plis de fond* in the literal sense, due to regional compression which buckled the whole thickness of the crust. This view appears to be confirmed by the fact that the trend of the arch cuts across dominant basement trends, although generally the tendency is for later faults to follow old lines. It is probably analogous to the Judean and Jordan arches which rose on either side of the Dead Sea rift at about the same time. The Dead Sea rift is a major discontinuity (geosuture) in the total crust along which, according to Henson (unpub. data, 1954-60), compressed crustal segments on either side may have buckled up because the discontinuity, yielding itself to slight transcurrent movement, interrupted normal fold propagation.*

Since the Gulf of Aden may follow an old geosuture (Henson, unpub. data, 1954-60), it is interesting to speculate on the possibility that the Somaliland plateau may be a counterpart, structurally, of the Hadramawt arch (s.l.) and that the present Gulf of Aden may have originated as a megasyntline between the two before it was broken down by rift faulting.

The stratigraphic record on the Somali side of the Gulf of Aden shows that in a part of north-central former British Somaliland, middle Eocene lower Daban in its type area is continuous with the overlying middle Daban of late Eocene and Oligocene age (Macfadyen, 1933). Since middle Daban equivalents are missing from the plateaus on either side of the Gulf of Aden, it is clear that at least part of this area was structurally depressed when the plateaus emerged, but the extent and trend of the depression are unknown (p. H40).

The Somaliland plateau itself trends west to east in two segments offset from each other meridionally, with a well-marked zone of intense post-Eocene "Red Sea"

faulting between them (Somaliland Oil Exploration Co., Ltd., 1954). As in southwest Hadramawt, slump faulting and antithetic rotation of blocks below the main escarpment of the plateau leave doubt as to the original form of the uplifts along most of its northern margin. But in northeast former British Somaliland, as in southeast Hadramawt, indications of original geanticlinal warping are found in some profiles. The plateau itself has gentle undulations comparable with those mapped on the Hadramawt side of the Gulf of Aden (Somaliland Oil Exploration Co., Ltd., 1954).

These observations suggest that the development of the Somaliland plateau was similar to that of its counterpart in the E.A.P. and that the geanticlinal arches on both sides of the Gulf of Aden were due to regional compression acting normally or obliquely to the Gulf axis in the west and to the old lines of weakness on the Dhufar-Kuria Muria and Socotra trends in the east.

Reactivated geosutures are thought to determine these trends, but basement "grains" within the arches, which are attributed to buckling of the crust as a unit, are not necessarily parallel. In Dhufar, for example, the east trend of the arch bears no relation to the basement grains (north, northeast, and northwest trends) in the limited exposures at Mirbāt, whereas in Hadramawt basement trends are highly variable; those trending east are exceptional. However, as much of the area now embraced by the arch is devoid of basement exposures, no conclusions are justified.

In former British Somaliland the main Red Sea* faulting occurred at the end of the middle Eocene (Somaliland Oil Exploration Co., Ltd., 1954). In southwest Hadramawt strong faulting on the same alignment occurred before Oligocene and Miocene marine incursions and may well have been contemporaneous with the Red Sea faulting in Somaliland.

It should be noted, however, that the most numerous and prominent faults are not strictly on the Red Sea trend (northwest) in the E.A.P. but follow a west-northwest trend, and they may have some different significance. The west-northwest trend is reflected in the basement trend of part of Jabal Sawād Bā Qutmi (p. H45) and in the basement structure of the Bulhar area of Somaliland; it may be in part a reactivated old trend. The west-northwest trending faults are particularly pronounced between the offset east and west sections of the Somaliland plateau (Somaliland Oil Exploration Co., Ltd., 1954) and at the western and

*The Red Sea group includes northwest, west-northwest, and north-northwest fault trends; only the latter is the true Red Sea trend (Erythraean). Other trends are the "East African" trend which is oldest (north, north-northeast) and conforms to the Afro-Arabian fracture pattern; the "Gulf of Aden" trend which is youngest (east-northeast); east; the east trend corresponds to the "Somali" trend of Wissmann; and the "Aulalic" trend (northeast) of Wissmann.

*These conditions have been reproduced in laboratory-scale experiments at the Iraq Petroleum Company Research Center in London.

eastern "pitch" of the South Ḥaḍramawt arch. Some of these faults in the E.A.P. are very long and straight, and their trend can be followed in Yemen, cutting across basement structure.

The faulting in these areas, therefore, may have developed during the culmination of the geanticlinal warping as a form of adjustment to differential crustal shortening which varied along the geanticlinal axes; or the faults may have determined the pitch of the arches. Thus, it might be suspected that some transcurrent movement, in which the Gulf of Aden trend may also have been involved, was associated with the faulting. If this is correct, it would explain a number of local structures indicative of compression ("block jostling") which occur in southwest Ḥaḍramawt and which probably originated at the end of the Eocene. These are seemingly anomalous in an area of predominant vertical movements and are discussed in the following paragraphs.

At Ḥulm Bā Tha'lab in the Wādī Ḥajr area, a structure some 30 km long and 8 km wide trends west-southwest, plunges east and flattens out westward. The core consists of basement extrusives which underwent multidirectional cleavage before peneplanation; the peneplain itself is now arched into a smooth domal form which the overlying sedimentary rock (from Jurassic to Eocene) follow concordantly in successive scarps down the flanks, and form a closure in the east. Dips are as high as 15°-20°. Two faults parallel to the axis bound the structure on both flanks, the northern dying out before it interrupts the full flank succession, and the southern cutting out the Jurassic. In the west the igneous core and the surviving flank strata are eroded and lost under a cover of blown sand. The trend of the feature is parallel to that of the South Ḥaḍramawt arch.

In the Wādī Kilyah area of the Wādī Ḥajr basin, a small thrust fault involves Cretaceous and Jurassic beds in an area where normal block faults prevail. It cannot be asserted that this structure originated during the late Eocene movements, but this seems probable in view of other evidence that minor horizontal displacements occurred at this time.

The Ḥulm Bā Tha'lab dome is of more than local interest because it suggests a mode of origin of some foreland folds (Henson, unpub. data, 1954-60). Lees (1952) accepted basement participation in foreland folding, visualizing anticlinal cores consisting alternately of upthrust slices or of bulges in the basement. But it is difficult to explain how gentle bulges such as the Ḥulm Bā Tha'lab dome, very small in relation to the total thickness of basement, could develop on the upper basement surface. The Ḥulm Bā Tha'lab dome

was first explained as the result of a diapiric (?) squeezing of the basement rocks between observed lateral faults, such movement being facilitated by intense cleavage. However, the smooth arching of the peneplain is evidence that does not support the theory of movement along multidirectional cleavage planes. Normal folding processes are ruled out by the massive nature of the basement material, in which there could be no adjustment along bedding planes; microshearing and mylonitization were not recognized. Plastic deformation could not normally be expected to occur in lightly loaded basement except under intense and locally applied stress. Such stress, however, should be revealed in flow structures, which have so far not been observed, and is incompatible with the preservation of cleavage planes.

In Yemen are certain anticlinal swells and fault folds and in the high plateau sparse diapiric folds with basement cores and Jurassic flanks (Lamare and others, 1930). One such example was attributed to squeezing up of the igneous core along two parallel faults (compare Ḥulm Bā Tha'lab). These phenomena were noted to be different from those characteristic of normally folded areas, not only by their lesser intensity, but also by their local occurrence as unaligned sporadic features in the block-faulted areas. The authors concluded by admitting the existence of squeezing movements that were due to the interplay of resistant blocks (block jostling) and that corresponded to a phase of compression resulting in vertical and tangential block movements. Foreland folds developed in this way would be analogous to the "diapiric buckling-folds" of Henson (*in* Fairbridge and Badoux, 1960).

Apart from structures of this type, the western part of the E.A.P. and parts of southeast Yemen and north-east W.A.P. are characterized by the occurrence of salt domes (p. H22), the extrusion of which is of some tectonic significance. Stratigraphically the salt has been shown to be of Late Jurassic age (p. H22, H23-H24).

All the domes, except those of the Al Minṭāq area, have had their overlying Cretaceous and Tertiary cover entirely removed, and they rise in flat-plain or sand-dune areas with only Pliocene and Recent deposits surrounding their Jurassic cores and rims. In the Al Minṭāq area, however, the domes which lie in deep wadyān have all arched up their Cretaceous and Tertiary overburden, the latter consisting mainly of some 250 m of massive limestone. There is no surviving evidence of the salt having burst through the massive Paleocene limestone cover, but the steep tilt outward of this limestone from the core indicates that it was strongly pushed up. The structures are in fact salt

blisters rather than piercement plugs, and they are oval or elliptical in shape.

The extrusion of salt clearly occurred after the Paleocene, probably at the end of the Eocene, although total sedimentary load was hardly sufficient to account for it without additional stimulus to start the movement (Henson, in Fox, 1959). There is no evidence of earlier movements in the stratigraphy, in spite of the opportunities provided by the terminal Jurassic normal faulting. Normal faulting alone was not, therefore, sufficient to initiate diapirism of the salt.

The E.A.P. domes are present in areas of post-Paleocene (east, northwest, and west-northwest trends) cross faulting which may have cut trap doors in the limestone roof to provide escape routes; but some tangential stress, due perhaps to horizontal components of fault movement, must have operated to cause salt diapirism. It is difficult to determine in the field whether there were any transcurrent, in addition to vertical, movements, because the surrounding beds are either generally flat and uniform (Al Mintāq area) or else absent. But the west-northwest-trending fault group is that which, for other reasons, has been assumed to be transcurrent. It is possible, therefore, that diapirism of salt and of basement rocks and the development of other compression structures in Ḥaḍramawt may be attributed to horizontal block movements associated with this faulting.

Geophysical surveys in the northern part of the E.A.P. provide evidence of other salt domes that have not broken through to the surface. These are thought to be Jurassic salt, and are probably still in the process of moving up under differential load pressure which becomes effective as soon as an incipient salt column has been established.

Although these various indications of local tangential compression and movement at the end of the Eocene are vague and inferential, they are consistent with the opinion expressed earlier that compression rather than tension was responsible for the development of the Ḥaḍramawt arch (s.l.), and it is possible that the minor compression structures recorded in Somaliland may have originated in related block-jostling movements.

During Oligocene and Miocene times subsidence and progressive marine ingressions from east to west occurred in the Gulf of Aden area. It was probably during this phase of relaxation from compressional uplift that major normal faulting, generally somewhat parallel to the axis of the folding (east-northeast and east trends), broke up the south flank of the Ḥaḍramawt arch (s.l.).

Proof of faulting at this time is lacking over most of the area affected where no rocks later than Eocene are exposed, but the coastal Oligocene and Miocene deposits have been tilted by fault movements that predate the Gulf of Aden faulting, *s.s.* These fractures have been attributed by Henson (unpub. data, 1954-60) to gravitational breaking down of the rising coastline and not to basement influences. This cannot be entirely true because some faults on these trends occur far north of the rift margins and must be due in part to some other cause, possibly to differential block movements associated with shallow fold-fault structures. Moreover, true east-northeast-trending "Adenean" faults (Henson, unpub. data, 1954-60) are present along the coast in the Mirbāt coast of Dhufar, although the North Ḥaḍramawt arch extension (the Kuria Muria trend) and the bathymetric contours swing to an east trend.

The same movements may be responsible for faults and gentle undulations parallel to the axis of the Ḥaḍramawt arch (s.l.) over the high plateau areas; in the Raydat al M'arrā area two rather flat folds some 50 km long, separated by a shallow syncline, occur north of the axial zone of the South Ḥaḍramawt arch and are expressed in lower Eocene beds; they occur en echelon, pitching eastward and flattening out westward.

Similar features occur in the Wādī al Jiz' basin on both side of the main Ḥaḍramawt-Al Jiz' synclinal axis, and are generally parallel in trend to that axis. In places they occur en echelon to each other, separated by flat synclines. Some have a small amount of closure, others are only noses. R. W. Wetzel and D. M. Morton (unpub. data, 1948-50) referred to them as fault structures. They are expressed in Eocene beds, though some involve Oligocene and Miocene deposits on their flanks, indicating their origin or reactivation in the late Tertiary.

Along the axial zone of the North Ḥaḍramawt arch in the Jabal Ḥabshiyah area, eastward-plunging noses expressed in Eocene beds occur south of the main axis of the arch.

There are other similar widely separated features of small dimensions, especially in the Al Mahrah area of the Southern Plateau. All appear to have associated faulting parallel to their axial trend, and faults trending east-northeast and east occur either on the flanks or in synclinal zones, and are undoubtedly associated with the formation of these structures.

Despite the important Oligocene and Miocene faulting there is no evidence of any volcanism having resulted.

The main (axial) Gulf of Aden trend is east-northeast—that is, parallel to the dominant basement grain of south W.A.P. (Weismann and others, 1942) and to

some late Miocene(?) faults near the western part of the South Hjadramawt arch, but oblique to the east trend of the arch and its step-fault system farther to the east.

Mapped faults on the east-northeast trend are fairly common, and long, straight stretches of coastline following this direction have clearly undergone relative elevation in Neogene to Recent times because Oligocene and Miocene deposits are involved in the uplift. There is little doubt that they mark important lines of profound Gulf of Aden faulting, *s.s.*, along which the land area rose far above the Gulf floor. The step faulting of the Hjadramawt arch (*s.l.*) is excluded from this group.

Although definite evidence to support the separation in time of the two systems is lacking, it is noted that the Gulf of Aden coastal trend abruptly truncates the South Hjadramawt arch and its faults in the Ra's Sharwayn-Ra's Fartak area, whereas east-northeast-trending faults occur across the North Hjadramawt arch in Dhufar.

In the former area there are also groups of Red Sea faults (northwest trend) which are considered later than the east-trending system and hence must be distinguished from the west-northwest-trending faults of Eocene date.

These generalizations apply, of course, only to systematic faulting which is complicated in places by abundant erratic fracturing on a small scale, or by rejuvenation of old faults.

No folding can, with confidence, be attributed to the Neogene and Recent movements, but some chaotic pseudofolding due to solution collapse is observed on a considerable scale in those parts of the high plateau where the lower (middle) Eocene Rus Formation gypsum has been dissolved below its cover of middle Eocene shale, marl, and limestone (Habshiya Formation) and then the collapsed cover has been recemented as pseudobeds.

During Neogene to Recent times much volcanism was associated with coastal faulting in the Gulf of Aden; some basalts occur further inland.

STRUCTURAL HISTORY

The Aden Protectorate lies on the gentle southeastward slope of the peneplaned Afro-Arabian shield which declines toward the southern part of the Middle East basin. Some authors have concluded that this slope was divided by the Jurassic trans-Erythrean trough (Lamare and others, 1930; Lamare, 1936; Arkell, 1932) into the Arabo-Nubian and Arabo-Somali masses (Picard, 1937; Mitchell, 1939), between which development of the volcanic Sabea block (Lamare and others, 1930; Picard, 1937) began late in the Cretaceous.

The oldest rocks seen in the peneplaned basement complex of the E.A.P. consist of Precambrian metamor-

phic rocks in the west, and similar rocks are exposed in the Mirbat area of Dhufar. A slightly younger basal extrusive series, covered by metasedimentary rocks that grade into nonmetamorphosed rocks, and associated younger intrusive igneous bodies make up the rest of the basement of southwest Hjadramawt (p. H9-H11). The dominant strike of original structure in the basement is north trending, with northwest, west-northwest, and east-northwest cross trends. Metamorphism increases from east to west in southwest Hjadramawt into the Wahidi State, and toward the W.A.P., with the result that confusion is possible between older and younger basement sedimentary rocks. Complexity in strike of folds and faults also increases westward.

Some time after the deposition of the youngest basement sediments and after some igneous intrusions had taken place, a period of powerful movements occurred, isoclinally folding the sedimentary rocks (and probably the volcanics). This diastrophism was accompanied or followed by dynamothermal metamorphism, probably in stages, and a system of intense multidirectional cleavage was imposed on all rocks. Further intrusive activity continued for some time thereafter.

The exposed series of Hjadramawt is assumed to rest on an older metamorphic series exposed in the W.A.P. and this in turn on a more massive basement which is not exposed and not involved in the close folding of the outcrops. It is suggested that the exposed basement sedimentary rocks of the E.A.P. occupy a complex faulted depression in which the higher incompetent strata were faulted and crumpled under their competent cover in a kind of passive adjustment to deep-seated and short-ranged block movements, compression being applied from the west. Repetition of stresses could account for secondary schistosity and for ultimate multidirectional cleavage, perhaps resulting from the operation of stress couples due to horizontal blockjostling. These stresses and the main compression need imply no great displacement or crustal shortening (F. R. S. Henson, unpub. data, 1954-60.)

Peneplanation or mature erosion of the basement followed. After peneplanation, subsidence occurred around the northern and eastern margins of the Arabo-Nubian mass, where Paleozoic, Mesozoic, and Tertiary seas advanced and retreated over its extremely gentle slope.

The earlier marine cycles left no record in southwest Arabia, however, but successive transgressions in Jurassic, Cretaceous, Paleocene, and middle Eocene times led to the deposition of mainly shallow-water sediments.

The age of the basement peneplain in the E.A.P. is pre-Jurassic and probably dates back originally to the Paleozoic. On this peneplain a Jurassic marine trans-

gression advanced from the south or southeast, but soon in the Late Jurassic, movements began to occur which caused the erection of a partial barrier that isolated an evaporitic basin inland. The movements are thought to have been largely block faulting. Later in the Late Jurassic the sea overcame the partial barrier and spread some way inland.

At the end of the Jurassic and in the earliest Cretaceous, uplift movements were again in evidence. In Somaliland this uplift followed the Gulf of Aden trend (Somaliland Oil Exploration Co., Ltd., 1954; Henson, unpub. data, 1954-60) and approximately follows the present line of the Somali plateau scarp. In the E.A.P. direct evidence is lacking for the assumption of a similar parallel uplift. Some indirect evidence suggests that uplift may have occurred, but this is by no means certain, because on both sides of the Gulf of Aden uplifts from which the Jurassic was removed diversified the main lines of the paleogeography, which is moreover concealed over large areas by later cover. In the E.A.P. and Dhufar the cross uplifts on a northerly trend (for example, Al Mukallā high) divide the region into north-south swells and depressions recognizable in coastal exposures by stratigraphic variations and inland by geophysical surveys.

During the Cretaceous the post-Jurassic erosion surface was tilted gently down toward the east and the Cretaceous marine transgressions advanced up this gentle slope from the east. Movements on a small, probably local, scale occurred along old lines of uplift. The Ra's Sharwayn area was uplifted in the Albian, and at Al Mukallā local uplift also occurred then and persisted until the end of the Cretaceous; the uplifted block trended north. Blocks were uplifted elsewhere also, some persisting throughout the Cretaceous, but in general Cretaceous sedimentation gradually levelled off the floor. This process retarded and accelerated as the successive cycles regressed and transgressed in the Cretaceous, owing to gentle epeirogenetic movements.

In Hajarawt, regional hiatus between the Cretaceous and Paleocene has been discovered from stratigraphic and paleontological studies, but the Paleocene follows the Upper Cretaceous in outcrop without any visible break. Local exceptions are found in the overlap of Paleocene on Lower Cretaceous at Al Mukallā and even on basement in the Wādī al Ghabar area. A gentle eastward tilting of the land surface occurred at this time and up this slope the Paleocene transgression advanced from the east.

In the Paleocene further slight tectonic movements began. In the north of the territory elevation of the North Hajarawt arch probably commenced with the end of slight terminal Cretaceous uplift; for a while it

formed a (submerged?) barrier to the advance of the Paleocene sea, but it was overcome soon after during the late(?) early Paleocene. Westward in the W.A.P. and Yemen the Paleocene sea thinned and pinched out against a shoreline made up of the volcanics that had commenced in part to be extruded as early as the Late Cretaceous.

Tertiary movements continued throughout the early Eocene and thickness and facies variations of the Eocene are related to the progressive development of the gentle geanticlinal Hajarawt arch (s.l.) (p. H14-H146) that spans the whole territory.

No upper Eocene deposits are known in the territory, or elsewhere in southwest Arabia, but they occur locally in Somalia; it was during late Eocene time that the Hajarawt arch (s.l.) attained its maximum development, with general emergence and erosion. The development of the Hajarawt (and Somali) arch is regarded as due to regional compression which buckled the whole thickness of the crust. Important block faulting and step faulting followed along the coastal belt, largely obscuring the south flank of the arch which, however, is clearly seen in relatively unbroken sections. The prevailing fault trends of the arch are evidently related to the fold strike. The faults appear to be predominantly of normal type, but some local compression structures were produced before or at the same time as the folding and faulting history.

Thus at Zulm Bā Tha'lab the basement peneplain with a cover of Jurassic to Eocene formations has been smoothly arched up and faulted, the uplift being on too large a scale to be explained by only vertical movement. At Wādī Kilyah a small flat thrust involves Jurassic and Cretaceous beds. In Yemen where such structures occur, including basement "diapirs," some tangential block movement in the basement is suspected (Lamare, and others, 1930).

The salt extrusions of the Shabwah-'Iyādh-Al Min-āq areas may have been stimulated by subsurface drag stresses of the same origin, the salt functioning as a gliding plane near basement level. The extrusions occurred after the Paleocene and made their way through the massive limestone cover, with no sign in the stratigraphy of earlier activity, in spite of opportunities provided by faulting at the end of the Jurassic. The domes occur in an area of post-Paleocene cross faulting which may have caused the fractures and breaks seen in the limestone roofs of the domes.

The emergence and upwarping of large areas in Arabia and in the Gulf of Aden region and the formation of the Hajarawt and Somali arches was followed by extensive Oligocene and Miocene "transgressions" which invaded inland into coastal depressions from a

Gulf of Aden already formed before late Tertiary rifting.

The emergence of Arabia then resumed and has continued until the present day, with coastal faulting, tilting of Oligocene and Miocene deposits, local Pliocene and Pleistocene marine incursions, and basaltic extrusions. Recurrent uplift and oscillations of the land surface in the Pliocene and Recent completed the history.

These events occurred all around the margins of the Arabian Peninsula and were not confined to the rift valleys (Red Sea and Gulf of Aden). It is indeed difficult to judge how much of the rift faulting was due to graben subsidence and how much to regional uplift of the bordering land surfaces.

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GEOLOGY OF THE ARABIAN PENINSULA

Jordan



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Geology of the Arabian Peninsula Jordan

By FRIEDRICH BENDER

GEOLOGICAL SURVEY PROFESSIONAL PAPER 560-I

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FOREWORD

This volume, *"The Geology of the Arabian Peninsula,"* is a logical consequence of the geographic and geologic mapping project of the Arabian Peninsula, a cooperative venture between the Kingdom of Saudi Arabia and the Government of the United States. The Arabian-American Oil Co. and the U.S. Geological Survey did the fieldwork within the Kingdom of Saudi Arabia, and, with the approval of the governments of neighboring countries, a number of other oil companies contributed additional mapping to complete the coverage of the whole of the Arabian Peninsula. So far as we are aware, this is a unique experiment in geological cooperation among several governments, petroleum companies, and individuals.

The plan for a cooperative mapping project was originally conceived in July 1953 by the late William E. Wrather, then Director of the U.S. Geological Survey, the late James Terry Duce, then Vice President of Aramco, and the late E. L. deGolyer. George Wadsworth, then U.S. Ambassador to Saudi Arabia, and Sheikh Abdullah Sulaiman, then Minister of Finance of the Government of Saudi Arabia, lent their support to the plan. In November of the following year, 1954, Director Wrather approved the U.S. Geological Survey's participation and designated G. F. Brown responsible for the western Arabian shield region in which he had previously worked under U.S. foreign-aid programs. In January 1955 F. A. Davies, Chairman, Board of Directors, Arabian-American Oil Co., approved Aramco's participation and appointed the late R. A. Bramkamp, chief geologist, responsible for compilation of the area within the Kingdom where the sediments crop out. This responsibility fell to L. F. Ramirez following the death of R. A. Bramkamp in September 1958.

R. A. Bramkamp and G. F. Brown met in New York in February 1955 and planned the program, including scales of maps, areas of responsibility, types of terrain representation, and bilingual names. Thus there was established a cooperative agreement between the Kingdom of Saudi Arabia, the U.S. Department of State, and the Arabian-American Oil Co. to make available the basic areal geology as mapped by Aramco and the U.S. Geological Survey.

The agreement specified publication of a series of 21 maps on a scale of 1:500,000, each map covering an area 3° of longitude and 4° of latitude. Separate geologic and geographic versions were to be printed for each of the quadrangles; both versions were to be bilingual—in Arabic and English. A peninsular geologic map on a scale of 1:2,000,000 was to conclude the project.

High-altitude photography, on a scale of 1:60,000, of the Kingdom of Saudi Arabia was initiated during 1949 by the Aero Service Corp. and completed in 1959. Both third-order vertical and horizontal control and shoran were utilized in compiling the photography. This controlled photography resulted in highly accurate geographic maps at the publication scale which then served as a base for the geologic overlay. The topography of the sedimentary areas was depicted by hachuring and that of the shield region by shaded relief utilizing the airbrush technique.

The first geographic quadrangle was published in July 1956 and the last in September 1962. While preparation of the geographic sheets was in progress, a need arose for early publication of a 1:2,000,000-scale peninsular geographic map. Consequently, a preliminary edition was compiled and published in both English and Arabic in 1958. The second edition, containing additional photography and considerable new topographic and cultural data, was published in 1963. The first of the geologic map series was published in July 1956 and the final sheet in early 1964. The cooperative map project was completed in October 1963 with

the publication of the 1:2,000,000-scale "Geologic Map of the Arabian Peninsula" (Miscellaneous Geologic Investigations Map I-270-A).

As work on the quadrangles progressed, geologists, companies, and governments working in areas adjacent to the Kingdom of Saudi Arabia were consulted by Aramco and invited to participate in the mapping project. The number of cooperating participants was expanded to 11, which included the operating oil companies in the peninsula and which are identified elsewhere in this text; the Overseas Geological Surveys, London; the Government of Jordan; F. Geukens, who had worked in Yemen; and Z. R. Beydoun, who had studied the Eastern Aden Protectorate. With the close cooperation of the authors, the new data were added to data already plotted on the base map of the Arabian Peninsula.

As the geological coverage of the peninsular map grew, the need for a text to accompany the map became apparent to both the U.S. Geological Survey and the Aramco geologists. Exploratory conversations were begun by Aramco with companies working in the other countries of the Arabian Peninsula for their participation in the preparation of a monograph on the geology of the Arabian Peninsula. Each author prepared a description of the geology of the area for which he was responsible, as shown in the sources of geologic compilation diagram on the peninsular map. The U.S. Geological Survey undertook the publishing of the volume as a professional paper, and the Government of Saudi Arabia was to finance its printing. It was early agreed that there would be no effort to confine the contributions to a standard format and that no attempt would be made to work out an overall correlation chart other than shown on the "Geologic Map of the Arabian Peninsula." Thus, the individual style of authors of several nationalities is preserved.

Cooperation and relations have been of the highest order in all phases of the work. The project would not have been possible without the full support of the U.S. Department of State, the Kingdom of Saudi Arabia, and all contributors. In fact, the funds which made publication of this volume possible were contributed by the Saudi Arabian Government.

The data provided by the maps and in the professional paper provide information for an orderly scientific and economic development of a subcontinent.

W. D. Johnston, Jr.

W. D. JOHNSTON, JR.,
Former Chief, Foreign Geology Branch,
U.S. Geological Survey.

O. A. Seager

O. A. SEAGER,
Arabian-American Oil Co. (Retired).

NOTE:

As stated in the Introduction, this report is based essentially on geologic data available in 1967 and incorporates stratigraphic and structural data resulting from investigations, sponsored by the United Nations Food and Agriculture Organization, of ground water and mineral resources from 1964 to 1969. Since then the Mining Division and the Department of Water Resources Authority in Jordan have undertaken extensive drilling and geophysical and geologic exploration programs which have yielded additional critical information. These data substantiate and refine the interpretation of several potential petroleum-bearing sedimentary basins, demonstrate large amounts of several metallic and nonmetallic mineral resources, and to some extent modify the tectonic-stratigraphic framework presented here.

With the new data, M. Malhas (1974, The tectonic and stratigraphic framework of Jordan and its implications regarding potential hydrocarbon accumulation: Jordan Nat. Resources Authority rept., in press) has synthesized the tectonic-stratigraphic relationships, documenting the presence of basins ranging from Palaeozoic to Tertiary, and described the petroleum geology. V. E. Swannow (1974, Recommendations for the study

and appraisal of oil shale deposits in Jordan: U.S. Geol. Survey open-file rept.) evaluated the oil shale resources and development programs of Jordan and concluded that the inferred reserves were very large. Recent work by the Natural Resources Authority (1972, The mineral prospects of Jordan: Jordan Nat. Resources Authority Mining Div., unpub. rept., 22 p.) indicates "prospective reserves" as large as 10 billion metric tons of shale containing 1 bil/metric ton (p. 20). V. F. Nimry (1972, The copper and manganese prospects of Wadi Arabah: Jordan Nat. Resources Authority Rept. on Phase One, 107 p. and map) reported on an extensive exploratory program by the Mining Division of the Natural Resources Authority; large resources of copper and manganese have been identified in the vicinity of Faynan on the east side of Wadi al 'Arabah. Other studies by the Mining Division indicate large resources of several nonmetallic minerals. More recent information on the availability of phosphate, glass sand, clay, tripoli, gypsum, ceramic and construction materials, and saline deposits are also available from the Natural Resources Authority (1972).

Project reports on investigations of these resources are on file in the Jordan Natural Resources Authority, Amman.

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GEOLOGY OF THE ARABIAN PENINSULA

JORDAN

By FRIEDRICH BENDER¹

ABSTRACT

The Hashemite Kingdom of Jordan covers an area of approximately 96,500 km² in the northwestern part of the Arabian Peninsula.

In southwestern Jordan, part of the Nubo-Arabian Shield is exposed. It is characterized by Precambrian plutonic and metamorphic rocks, and by some minor occurrences of upper Proterozoic sedimentary rocks. Cambrian, Ordovician, and Silurian sandstone and shale of continental and marine origin have a maximum thickness of 1,800 m and unconformably overlie the rocks of the Precambrian basement complex.

A belt of sedimentary rocks deposited chiefly on the stable shelf area of the Tethys Sea borders the northern fringe of the shield. Most of southeastern and central Jordan is within this belt. It is a zone of interfingering sedimentary rocks of continental, littoral, and neritic origin, rapid lateral facies changes, and many stratigraphic unconformities caused by pulsation and, at certain periods, transgression and regression of the Tethys Sea. Regionally, the marine influence on the deposition increases toward the north and west. The total thickness of all post-Proterozoic sedimentary rocks is 2,000–3,000 m; it exceeds 4,000 m in the baylike sedimentary basin of Al Jafr in south-central Jordan, and 5,000 m in the Al Azraq-Wādi as Sirbān Basin in north-central Jordan. These basins strike northwest and thus seem to merge with the unstable shelf area of the Tethys Sea in the northwest.

In the transition zone to, and in the area of, the unstable shelf in northwestern, northern, and probably northeastern Jordan, neritic and bathyal sedimentary rocks form the major part of the post-Paleozoic rocks. Here, the stratigraphic sequence is more complete, unconformities are fewer, and lateral facies changes are less pronounced than in the stable shelf area to the south and southeast. In northwestern Jordan, west of the Jordan River, the total thickness of sedimentary rocks above the Precambrian basement may be as much as 7,000 m; in the Dead Sea area of the Wādi al 'Arabah-Jordan Rift province, repeated structural subsidence resulted in the accumulation of sedimentary rocks as much as 10,000 m thick.

No evidence is known of post-Proterozoic structural movements characteristic of alpine orogenesis. The crustal movements affecting the country since the Cambrian were gentle regional tiltings (epeirogenic movements) and a combination of faulting, block folding, and taphrogenic movements. The

majority of structural features were caused by tensional forces. Evidence of compression is rare and chiefly restricted to west Jordan and to north Jordan east of the Rift.

Major volcanic activity occurred during the late Proterozoic and Early Cambrian (quartz porphyries, Wādi al 'Arabah), during the Late Jurassic(?) and Neocomian (mafic and intermediate eruptive rocks, Wādi al 'Arabah and west of the Jordan River), and during the Neogene (includes Miocene and Pliocene as used in this report) and Pleistocene (extensive basalt volcanism).

INTRODUCTION

SCOPE OF CONTRIBUTION

This report describes the geology of that part of the northwestern Arabian Peninsula, the Hashemite Kingdom of Jordan, which was mapped by a geological mission of the Geological Survey of the Federal Republic of Germany, 1961–67. The mapping was done at scales of 1: 25,000, 1: 60,000, and 1: 100,000 and later compiled at a scale of 1: 250,000 (Bender and others, 1968). This map differs in certain areas from Quennell's (1966) geologic map of Jordan east of the Wādi al 'Arabah-Jordan Rift, which covers approximately the western half of Jordan, and which was incorporated in the 1: 2,000,000-scale geologic map of the Arabian Peninsula (U.S. Geological Survey and Arabian-American Oil Company, 1963).

The geographic names in this report conform to the Jordan Gazetteer of 1971, which lists names approved by the U.S. Board on Geographic Names; however, for several names the more popular spelling is given in parentheses both in the report and on plate 1.

PREVIOUS WORK

The literature dealing with the geology of Jordan is surprisingly extensive. It has been recently compiled, and an account of the history of geological

¹ Geological Survey of the Federal Republic of Germany.

research has been given by Bender (1968a). Therefore, only some significant publications are cited herein.

Seetzen (1810) gave one of the first accounts of a geographic reconnaissance survey; he lost his life on his last expedition (Kruse, 1854-55). In 1837, von Schubert and Roth discovered that the Dead Sea level is considerably lower than the level of the Mediterranean (Hull, 1886, p. 12). Bertou (1839) is reputed to have been the first traveller to travel the length of the Wādī al 'Arabah from the Dead Sea to the Gulf of Aqaba. Russegger (1847) made several expeditions to the "Holy Land" and published a "geognostic" map of Arabia Petraea. Under the leadership of U.S. Navy Lt. Lynch (1852), a survey was undertaken to explore the Dead Sea and the River Jordan. Later, Ritter (1848-55), vom Rath (1881), Fraas (1867a, b), Milne (1875), and Lartet (1876) discussed geologic problems of the Jordan area. The contributions of Hull (1886) incorporated many detailed records on geologic observations and a geologic map of Wādī al 'Arabah.

From about 1890 to 1914, Max Blanckenhorn was engaged in geologic research in Palestine and Transjordan. He achieved a comprehensive knowledge of the country and documented his observations in many publications (Blanckenhorn, 1903, 1912, 1914). During that time, the Hejaz Railroad from Damascus (Syria) via 'Ammān, Ma'an, and Al Mudawwarah to Al Madinah (Saudi Arabia) was planned and constructed. The area thus became more accessible, and geologic research increased considerably (Auler, 1908; Musil, 1907, 1911; Krusch, 1911; Dienemann, 1915; Fuchs, 1916; Kober, 1919; Schwöbel, 1921).

During the period of the British Mandate, King (1923), Cox (1924, 1925, 1932, 1934), Muir-Wood (1925), Wagner (1934), Richter and Richter (1941), and Avnimelech (1945) published reports on the paleontology of Cambrian, Triassic, and Jurassic rocks. Regional geologic problems were discussed by Krenkel (1924, 1925, 1941) and Hennig (1938). G. S. Blake, as geologist of the British Mandate Government, carried out systematic surveys on mineral and ground-water resources and recorded his findings in many contributions (Blake, 1928, 1930, 1936, 1939; Ionides and Blake, 1939; Blake and Goldschmidt, 1947). Blake lost his life while on a field survey in the Wādī al 'Arabah.

Willis (1928) and Wellings (in Willis, 1938) investigated problems on the evolution of the Jordan Rift. Structural phenomena were also discussed by

Dubertret (1932), who also published geologic maps of the region (Dubertret, 1959, 1962). Since 1928, important contributions to the knowledge of the geology in the Jordan area have been made by Picard (1928, 1931, 1941, 1943, 1953, 1965). Shaw (1947, 1948) published a geologic map of southern Palestine and gave an account on the geology and mineral resources of Palestine. A similar contribution was made by Quennell (1951, 1956) for the territory of Transjordan. Quennell's maps and geologic findings formed the main basis of Burdon's "Handbook of the geology of Jordan . . ." (1959). A significant contribution, especially on stratigraphic correlation, was published by Wetzel and Morton (1959).

During the last 20 years, geologic consulting that concerned projects for economic development has played an increasing role. Generally, the results are in unpublished reports for the Government of Jordan—for example: Reports of the Transjordan Petroleum Development Co., Ltd. (1947-49)¹; E. W. Pauley Oil Exploration and Phillips Petroleum Co. (1956-60)²; J. W. Mecom Oil Co. (1964-66)³; Mackay & Schnellmann (1954, 1957)⁴; Parsons Corp. (1963)⁵; Gold (1964)⁶; Wilson and Wozab (1954); Baker and Harza Engineering Co. (1955)⁷; Hunting Technical Services, Ltd. (1956, 1965)⁸; Sir M. Macdonald & Partners (1965)⁹; Rofe & Raffety Consultant Engineers (1963, 1965)¹⁰; the

¹ Transjordan Petroleum Development Co., Ltd. 1947-49. Unpub. rept., Jordan Nat. Resources Authority, Amman, Jordan.

² E. W. Pauley Oil Exploration and Phillips Petroleum Co. 1956-60. Unpub. rept., Jordan Nat. Resources Authority, Amman, Jordan.

³ J. W. Mecom Oil Co. 1964-66. Unpub. rept., Jordan Nat. Resources Authority, Amman, Jordan.

⁴ Mackay & Schnellmann. 1954. Mineral resources in Jordan. London, Mackay & Schnellmann Consulting Economic Geologists, unpub. rept.

⁵ Mackay & Schnellmann. 1957. Phosphate resources in Jordan. Roshafa: London, Mackay & Schnellmann Consulting Economic Geologists, unpub. rept.

⁶ Parsons Corporation, 1963. Exploration and geology, v. 2 of El Hass phosphate project: Los Angeles, Calif., Parsons Corp. Engineering, unpub. rept. 3166-1, Jordan Nat. Resources Authority, Amman, Jordan.

⁷ Gold, O., 1964. The Wadi Araba copper exploration, Jordan—report on phase A: Köln, Germany, Ingenieurberatung für Bergbaufragen, unpub. rept. for Jordan Government, Jordan Devel. Board, Amman, Jordan.

⁸ Baker, M., and Harza Engineering Co., 1955. Yarmouk-Jordan Valley project, master plan report: Unpub. rept. for the Jordan Government, Jordan Nat. Resources Authority, Amman, Jordan, v. 1-13.

⁹ Hunting Technical Services, Ltd., 1956. Range classification survey of the Hashemite Kingdom of Jordan: London, Hunting Tech. Services, Ltd., unpub. rept., Jordan Nat. Resources Authority, Amman, Jordan.

¹⁰ Hunting Technical Services, Ltd., 1965. Wadi Dhuail investigation: London, Hunting Tech. Services, Ltd., unpub. rept., Jordan Nat. Resources Authority, Amman, Jordan.

¹¹ Sir M. Macdonald & Partners, 1965. East bank Jordan water resources, summary report: Sir M. Macdonald & Partners, unpub. rept. for the Jordan Government, Jordan Nat. Resources Authority, Amman, Jordan.

¹² Rofe & Raffety Consultant Engineers, 1963. Jerusalem and district water supply, geological and hydrogeological report: London, Rofe & Raffety Cons. Engineers, unpub. rept. for Jordan Central Water Authority.

¹³ Rofe & Raffety Consultant Engineers, 1965. Nabulus district water resources survey: London, Rofe & Raffety Cons. Engineers, unpub. rept. for Jordan Central Water Authority.

reports of the United Nations Food and Agriculture Organization (UNFAO) "Sandstone Aquifer Project in southeast-Jordan"; Lloyd (1969); Parker (1969); and the reports of the German Geological Mission (1961-67).

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The author wishes to express his appreciation and thanks to Mr. O. A. Dokhgan, the general director for many years of the Natural Resources Authority of the Hashemite Kingdom of Jordan, who promoted all efforts concerning geologic research in Jordan. The author furthermore greatly appreciates and thanks his colleagues of the German geological mission who shared in the field and office work in Jordan from 1961 to 1967: A. Abdullatif, D. S. Ahmad, G. van den Boom, R. Busse, F. Z. Dajani, A. Futian, J. Grieger, F. Grüneberg, M. Haddadin, W. Heimbach, H. Ibrahim, K. Jeresat, K. M. Khdeir, M. Lahloub, R. Lenz, W. Lillich, M. Nuseibeh, M. Ruef, S. S. Salem, O. Suwwan, B. F. Sunna, Z. Tuqan, and G. Wiesemann.

Special acknowledgment goes to Mr. W. Barber, project manager of the UNFAO "Sandstone Aquifer Project in southeast-Jordan" for many discussions related to the geology of Jordan, and for access to his unpublished material.

Naturally, this paper incorporates results of work by many more geologists who were involved in the collection and processing of data presented here. Each of these contributions is cited individually.

GENERAL GEOMORPHOLOGY

The Hashemite Kingdom of Jordan covers an area of approximately 96,500 km² in the northeastern part of the Arabian Peninsula. In contrast to the more uniform and monotonous morphology of most of the interior of the Arabian Peninsula, the western and northwestern parts, including the territory of Jordan, are morphologically distinctive. Jordan may be divided into seven physiographic provinces, which coincide with geologic provinces (fig. 1):

- Southern Mountainous Desert;
- Mountain Ridge and Northern Highlands East of the Rift;
- Central Plateau (includes Al Jafr and Al Azraq-Wādī as Sirhān Basin);
- Northern Plateau Basalt;
- Northeastern Plateau;
- Wādī al 'Arabah-Jordan Rift;
- Highlands West of the Rift.

The Southern Mountainous Desert occupies the area south of the west-northwest-striking escarpment of Ra's an Naqb, and extends southward into Saudi Arabia. Between Al 'Aqabah and Al Quwayrah where igneous rocks of the Precambrian basement are exposed, the country is rough, and steep mountains rise to 1,550 m above sea level (fig. 2). Farther east, Paleozoic and Mesozoic sandstone overlies the Precambrian basement complex, and from Kawn Ramm (Wādī Ramm) to the east they cover it completely. The sandstones also form steep bizarre cliffs (fig. 3) and mountains more than 1,700 m in altitude (Jabal Ramm, 1,754 m). Closer to the disused Hejaz Railroad (Al Mudawwarah) and farther east (Jabal at Tubayq), an inselberg landscape of table mountains and large depressions are the dominant topographic features (fig. 4). Broad, generally flat areas near the base level of erosion indicate that the mature stage of the arid erosion cycle has been reached in this region. The debris of arid weathering, drifting sand, and pelitic sediments in extensive mudflats cover the depressions and form very thick fill in erosion channels of the Pleistocene pluvial periods. Drainage in the western part of this physiographic province is to the south into the Gulf of Aqaba and is still actively cutting headward. In the eastern part, drainage turns southeast into the flat's south of Al Mudawwarah and east into Wādī as Sirhān Basin.

The Mountain Ridge and Northern Highlands East of the Rift is a coherent physiographic feature, in spite of its varied geologic character. It stretches north-northeast to north for about 370 km from the Gulf of Aqaba to Lake Tiberias; in general, it slopes gently toward the Central Plateau in the east, whereas it slopes very steeply toward the Rift province in the west (fig. 5). Because the base level of erosion in the Rift province has been lowered by continuing structural subsidence, the westward drainage of the Mountain Ridge province has been rejuvenated frequently. Thus, the streams have cut farther and farther eastward into the Central Plateau, capturing additional areas for the drainage basin of the Rift (Burdon, 1959, p. 12). The highest altitudes in the country (about 1,850 m) are in the southern part of the Mountain Ridge province, in the Jibal ash Sharāh.

The Central Plateau is bordered on the west by slopes that rise westward to the Mountain Ridge province; in the north and in the east, the Central Plateau falls to the flat, wide southeast-striking Al Azraq-Wādī as Sirhān Basin, which includes the oasis of Al Azraq in its northeastern part. The hori-

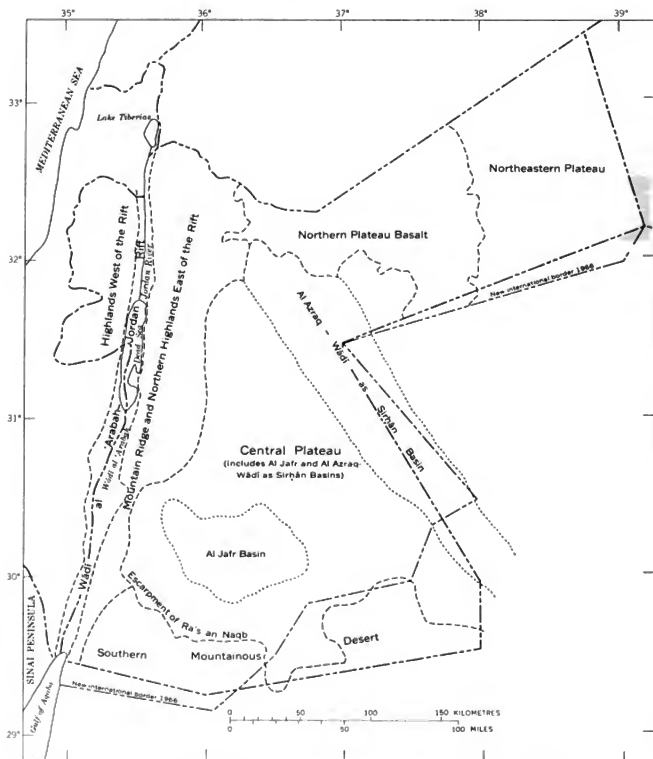


FIGURE 1.—Index map showing physiographic-geologic provinces, Jordan.

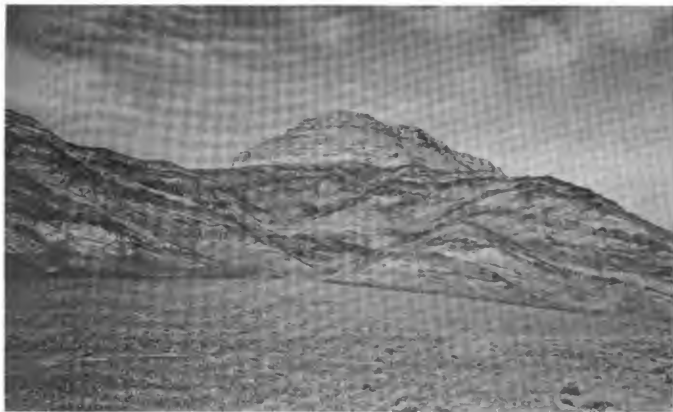


FIGURE 2.—Precambrian granodiorite and dikes and overlying Cambrian sandstone, approximately 5 km north-northwest of Al Quwayrah, southern Jordan.



FIGURE 3.—Cambrian and Lower Ordovician sandstone, approximately 8 km south-southeast of Ramm police station (long 35°25' E., lat 29°35' N.), southern Jordan.

zonal or gently dipping limestone, marl, and chert beds of the Upper Cretaceous and lower Tertiary sequence form tableland scarps; chains of outliers (fig. 6) are partly covered or surrounded by the debris of arid weathering. The outliers reach al-

titudes of about 1,000 m above sea level. To the south, the altitude of the Central Plateau gradually lowers to about 850 m above sea level and is lowest in the wide Al Jafr Basin, which is about 150 km long in a northwest direction and about 100 km wide. The central part of this basin is an extensive mudflat (240 km²). Farther south, the altitude of the Upper Cretaceous and lower Tertiary rock sequence of the Central Plateau is more than 1,500 m at the escarpment of Ra's an Naqb, the boundary between the Central Plateau and the Southern Mountainous Desert provinces. Areas of many hundreds of square kilometers in the central parts of the Central Plateau are covered by desert pavement consisting of wind-eroded chert residue, the flint-strewn "Hamada" desert. Drainage in the western part of the Central Plateau is to the west where extensive drainage areas have been captured for the Rift by the headward erosion of the Wādī al Mawjib, Wādī al Karak, Wādī al Ijasā, and Wādī Dānā drainage systems. In the southern part of the Central Plateau, drainage is from all sides

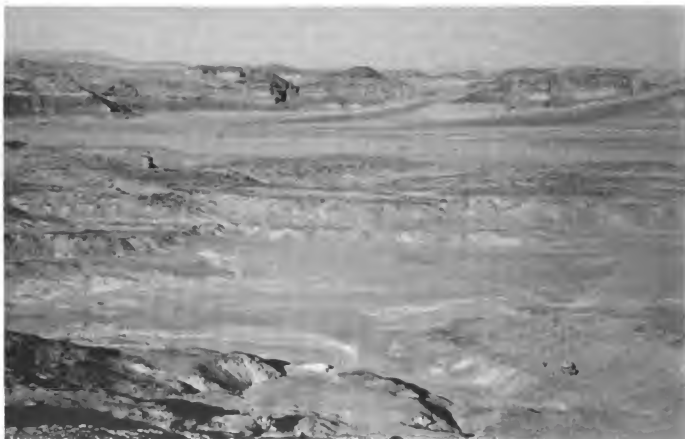


FIGURE 4.—Middle and Upper Ordovician sandstone and shale, approximately 10 km northwest of Maḥaṭṭat al Mudawwarah, southern Jordan.



FIGURE 5.—Beginning of flexure in Upper Cretaceous limestone and marl, east of the Al Lisān Peninsula. Dead Sea in the background.

to the center of the Al Jafr Basin; in the east and north, drainage is northeast into the Al Azraq-Wādī as Sirḥān Basin.

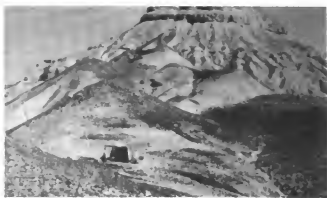


FIGURE 6.—Outlier Tuwayyil ash Shihāq of Upper Cretaceous and lower Tertiary limestone, marl, and chert, approximately 30 km southeast of Maḥaṭṭat al Ḥasā, central Jordan.

The Northern Plateau Basalt province in Jordan covers an area of approximately 11,000 km², east of the northern part of the Al Azraq-Wādī as Sirḥān Basin. The Plateau Basalt forms an almost inac-

cessible landscape of flows, fissure effusions, and isolated volcanoes (fig. 7). The basalt of many flows has been cracked by insolation and broken into blocks. This shield of basalt gradually lowers from altitudes of about 1,100 m at the Syrian-Jordanian border on the north to approximately 550 m in the south, close to the Wādī as Sirhān Basin. Drainage is south and southwest to Wādī as Sirhān; in the eastern part of the Plateau Basalt drainage is east and southeast.

East of the Plateau Basalt, the Northeastern Plateau province extends as a monotonous quasi-plateaued landscape far eastward across the Iraq border, north into Syria, and south into Saudi Arabia. This area is almost entirely occupied by calcareous and siliceous lower Tertiary sedimentary rocks, locally covered by upper Tertiary calcareous and sandy rocks and by Quaternary unconsolidated sediments. The drainage pattern obviously follows zones of structural weakness—mainly northwest, and, less pronounced, north-northwest and east-northeast (fig. 8).

The Wādī al 'Arabah-Jordan Rift (the Rift province) is a narrow depression that extends from the Gulf of Aqaba for approximately 360 km north to Lake Tiberias; it represents but a small fraction of

the East African-Asia Minor Rift system. Unconsolidated sediments of Neogene (Miocene and Pliocene) and, chiefly, Quaternary age occupy most of the floor of the Rift province. The floor of the Rift rises gradually from the Gulf of Aqaba to altitudes of 250 m above sea level at the watershed of Jabal ar Rishah in the central Wādī al 'Arabah. From there the floor falls gently northward to the surface of the Dead Sea, 392 m below sea level. The Dead Sea covers an area of 997 km²; it is 80 km long and averages 15 km wide. North of the Al Lisān Peninsula (fig. 9), the Dead Sea reaches its maximum depth of 401 m; thus, the maximum depth of the depression is 793 m below sea level. From the Dead Sea, the direction of the depression turns slightly from N. 15° E. to about N. 5° E. From the mouth of the Jordan River at 392 m below sea level, the 105-km-long Jordan River valley rises to 212 m below sea level at Lake Tiberias.

In the Highlands West of the Rift, structural upwarps (of a folded and faulted, mainly Upper Cretaceous-lower Tertiary rock sequence) and drainage systems (eastward to the Jordan River valley and westward to the Mediterranean Sea) have combined to form a mountainous diversified landscape (fig. 10). The watershed between the



FIGURE 7.—Basalt flow cracked by insolation, blocks subangularly shaped by wind corrosion; approximately 200 km east of 'Ammān, northeast Jordan.

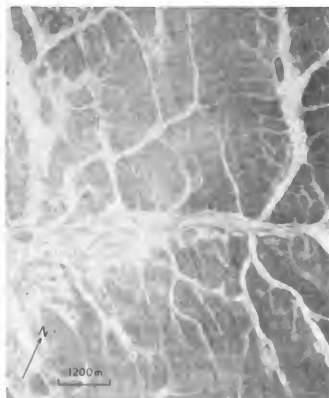


FIGURE 8.—Aerial view of wadis and mudflats that follow structural pattern in Tertiary limestone; approximately 250 km east-northeast of Al Mafrāq.

Dead Sea catchment area and the Mediterranean Sea trends approximately north-northwest from the Al Khalil (Hebron) region through Bethelēm-Jerusalem-Rāmallah to the Nābulus (Nablus) region, and reaches altitudes of about 1,000 m.

GEOLOGIC HISTORY AND PALEOGEOGRAPHY

The small exposures of highly metamorphosed rocks along the southern Wādī al 'Arabah seem to represent the remnants of early(?) Proterozoic geosynclinal sedimentation and volcanism. The intrusion of gabbroic rocks, diorite, quartz diorite, granodiorite, and aplite granite, which are the main constituents of the Precambrian basement complex in south Jordan, may be considered the cause of their katazonal metamorphism. As isotope determinations have revealed, the plutonic rocks are of late Proterozoic age. The age succession of the different types of igneous rocks has not been clarified. A great many differentiated dike rocks were intruded at different times into the solidified plutonites, along dominant zones of tension that strike



FIGURE 9.—The Wādī al 'Arabah-Jordan Rift province at its lowest point as viewed from the west. Upper Pleistocene terraced coarse clastic deposits are in foreground; opposite shore of the Dead Sea is the eastern edge of the rift valley showing a Triassic, Jurassic, and Cretaceous rock sequence.

northeast, east, and north. The number of dikes per square kilometer of exposed Precambrian basement complex increases considerably from south-east Jordan westward toward the Wādī al 'Arabah-Jordan geosuture (zone of the structural weakness).

Uplift and erosion preceded the deposition of sediments of latest Proterozoic age, which were affected merely by epizonal metamorphic processes and do not indicate alpine-type orogenesis. All these Proterozoic rocks were then intruded by many differentiated dike rocks.

At the beginning of the Cambrian, a peneplain formed in southern Jordan east of the Rift; highly



FIGURE 10.—Upper Cretaceous rocks, western edge of Wādī al 'Arabah-Jordan Rift province, Mount of Temptation west of Arihā (Jericho).

metamorphosed "roof rocks" and remnants of upper Proterozoic sedimentary rocks were eroded away. In the area of the Wādī al 'Arabah-Jordan geosuture, however, a surface of pronounced relief was cut in the Precambrian rocks, and quartz porphyry lavas seem to have erupted dominantly along this geosuture from the latest Proterozoic until deposition of Cambrian sediments.

Because of Precambrian tectonism, the metamorphosed rocks and upper Proterozoic sedimentary rocks in the area of Wādī al 'Arabah were preserved from complete erosion prior to the deposition of Cambrian sandstone. For this and other reasons, it is therefore thought that the formation of the Wādī al 'Arabah-Jordan geosuture dates back to Precambrian time.

Since the beginning of the Cambrian, the paleogeographic evolution of Jordan has been influenced by three dominant features: (1) The Tethys Sea in the west and northwest, which transgressed several times over parts of, or over all of Jordan, (2) the Wādī al 'Arabah-Jordan geosuture, which separates the Palestine block on the west from the Trans-

Jordan block on the east, and (3) the Nubo-Arabian Shield in the southeast and south, from which mechanical and chemical weathering products were transported onto the shelf of the Tethys Sea and where, during certain periods, continental clastic sediments were deposited.

The clastic sedimentary rocks of the Lower Cambrian are of continental origin, insofar as is known from exposures in south Jordan and along the Rift. These Lower Cambrian rocks overlie either peneplained Precambrian plutonites or, as in the Wādī al 'Arabah zone of the geosuture, a surface of pronounced relief cut in different Precambrian rocks.

During the latest Early to Middle Cambrian, an early transgression of the Tethys Sea advanced to the east side of the central part of the Wādī al 'Arabah. The pattern of different lithofacies (marine calcareous, marine sandy, continental sandy) was influenced by the north-south course of the geosuture between the Palestine and Transjordan blocks (fig. 11). A regression is indicated in the Middle and Late(?) Cambrian by continental sandstones above the Tethyan marine sedimentary rocks.

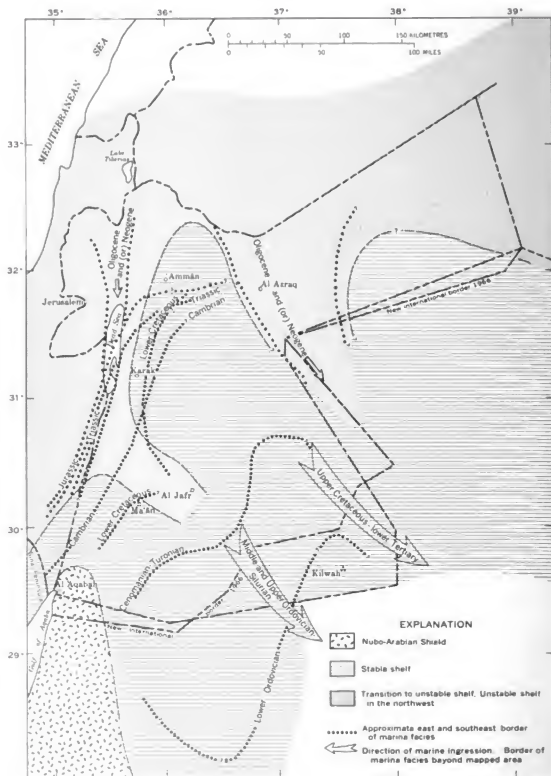


FIGURE 11.—Paleogeography of Jordan.

During the Early Ordovician, the Tethys Sea again transgressed over flat land areas, entering southeast Jordan and northwest Saudi Arabia, far beyond its Cambrian shoreline. In a shallow marine environment of deposition, mainly fine-grained sandy and argillaceous material accumulated during the Middle and Late Ordovician and the Early Silurian. In southeast Jordan, continental influence on the sedimentation is suggested by a red-brown sandstone sequence between the marine Lower Silurian and the marine Upper Silurian clastic rocks. The marine environment of deposition continued also in the Early Devonian. Calcareous and sandy rocks of this age are found about 100 km southeast of the southeast corner of Jordan. Middle and Upper Devonian sedimentary rocks have not been identified.

Carboniferous (lower Westphalian A-Namurian-upper Viséan) sandstones and calcareous sandstones were deposited in a littoral(?) continental environment in north Jordan and probably also in west Jordan. Rocks of Permian age have not been confirmed.

Another transgression of the Tethys Sea to the southeast occurred during the Early and Middle Triassic. The sea advanced from the west and northwest to the area just east of the Dead Sea, where Triassic littoral, lagoonal, and continental(?) sedimentary rocks disconformably overlie lower Paleozoic clastic rocks.

After a regression during the Late Triassic and Early Jurassic (Rhaetian and Liassic), the ocean advanced once more during the Middle Jurassic. Jurassic shorelines probably were just west of and approximately parallel to the borders of the Triassic transgression, whereas erosion continued on the land farther east and south. Again, the eastern borders of the marine depositional environment and the thickness of the deposited sediments were remarkably influenced by the meridional zone of structural weakness (fig. 11).

Renewed epeirogenic uplift and erosion, and local volcanism, probably during the Late Jurassic (Kimmeridgian), preceded Early Cretaceous deposition. Dominantly clastic rocks of Early Cretaceous age therefore overlie the Paleozoic, Triassic, or Jurassic formations with a regional angular unconformity. During the Early Cretaceous, the marine depositional environment dominated the northwest part of Jordan, and a transgression during the Albian reached the area east of the Jordan River. Farther east and to the south, clastic sediments of continental origin were deposited.

Beginning in the Late Cretaceous (Cenomanian),

a regional transgression started to spread over land areas far beyond the borders of the Albian sea. Closer to the Nubo-Arabian Shield in the southeast, however, the continental depositional environment of sandy sedimentation, which formed in the Early Cretaceous, continued in the Late Cretaceous, including the Santonian. The marine calcareous, marly, siliceous rock units of the Cenomanian, Turonian, Santonian, Campanian, and Maestrichtian therefore overlie these continental sandstones with onlap toward the southeast. In the areas occupied by the sea, great thicknesses of sediments accumulated in basins, particularly along the Wādī al 'Arabah-Jordan geosuture, and in the Al Jafr and Al Azraq-Wādī as Sirhān Basins (fig. 11). The pattern of gentle swells characterized by phosphorites, oyster lumachelles, and chert layers, and of local euxenic basins characterized by thick bituminous limestones and marls, was pronounced during the Late Cretaceous (Campanian, Maestrichtian, and Danian) and continued during the Paleocene and early Eocene.

During the late Eocene, thin calcareous sediments were deposited in a shallow marine depositional environment. They are found only locally in the basins where subsidence continued, but all of Jordan probably remained covered by the sea.

During the Oligocene, taphrogenic (rift-forming) structural movements started on the southern east side of the Wādī al 'Arabah-Jordan geosuture and resulted in uplift, emergence, and continental erosion. The subsequently formed graben zone (rift valley), and extensive parts of north and northeast Jordan still remained covered by the Tethys Sea.

In the Neogene, paleogeographic conditions in the Wādī al 'Arabah-Jordan geosuture were dependent on the relation between taphrogenic subsidence and sediment accumulation. The rift valley which formed along the geosuture was either occupied by freshwater lakes draining west to the Tethys Sea, or it formed an inland depression of terrestrial or lacustrine sedimentation, or it was entered by marine waters. During a time in the Miocene-Pliocene, the Mediterranean Sea may have been linked with the Red Sea through the Gulf of Aqaba and Wādī al 'Arabah-Jordan rift valley and through the Beisan depression (pl. 3). A Miocene transgression from the north reached to the Al Azraq-Wādī as Sirhān Basin and to northeast Jordan beyond the Djebel ed Drouz basalt flows. In the area of deepest structural subsidence within the rift valley (Dead Sea-Ghawr as Šāfi area), evaporites about 4,000 m thick were deposited during the Miocene(?)–Pliocene–early Pleistocene(?). During the Pliocene–Pleistocene time

transition and intra-Pleistocene time, several phases of major taphrogenic movements occurred. During Villafranchian and Acheulian time thick fluvialacustrine sediments and volcanic material accumulated in the Wādī al 'Arabāh-Jordan Rift. Lacustrine sediments and fluvial sand, gravel, and conglomerate also characterize late Pleistocene and Holocene deposition within the graben.

Apparently during the middle Tertiary, folding, mainly in the west and in the north, was contemporaneous with and related to the beginning of the Jordan Rift taphrogenesis. The folding was followed by regional arching, and, during the Pliocene and Pleistocene, by several phases of major faulting.

In the areas adjacent to the rift valley and in southeast Jordan, which had been emergent since the Oligocene, and in the large basins in northern, northeastern, and eastern Jordan, which emerged not earlier than the Miocene and Pliocene(?), denudation has prevailed until the present time. Weathering products were transported in great quantities either into the rift valley or into the extensive depressions in east Jordan. These depressions were partly covered by fresh-water or brackish-water lakes during pluvial periods in the Pleistocene; fluvial conglomerates spread over extensive areas along the eastern slopes of the highlands which border the east side of the Wādī al 'Arabāh-Jordan Rift province.

PRECAMBRIAN BASEMENT COMPLEX METAMORPHIC ROCKS

Small outcrops of garnet-biotite gneiss, biotite-hornblende gneiss, and biotite schist have been reported from the east side of the southern Wādī al 'Arabāh (Lartet, 1869; Blake, 1936, 1939; Burdon, 1959; Bender 1968a). These rocks are found as stopped blocks, or inclusions, within the surrounding Precambrian intrusive rocks—for example, the well-exposed rocks in the lower course of the Wādī Abū Barqā north of Gharandal (fig. 12).

IGNEOUS ROCKS

The important Precambrian igneous rocks have been distinguished on the "Geological Map of Jordan" sheet "Aqaba-Ma'an" (Bender and others, 1968), and are described by Bender (1968a) and van den Boom and Röscher (1969).

Hornblende and hornblende gabbro were found west of the Jabal al Muḥtādī, on the western slopes of the Jabal Ḍarbah, in the Wādī Ḍarbah, and on the west side of the Tilāl Turaybīn—all on the east



FIGURE 12.—Biotite schist in aplite granite; lower Wādī Abū Barqā, east side of central Wādī al 'Arabāh.

side of the southern Wādī al 'Arabāh. Three potassium-argon age determinations by Lenz and others (1972) resulted in ages of 611 ± 9 million years (hornblende), 584 ± 8 m.y. (biotite), and 564 ± 12 m.y. (biotite).

Diorite in the lower Wādī Qunayyah near the southeast shore of the Dead Sea was also dated by Lenz and others (1972) as 594 ± 8 m.y. and 585 ± 8 m.y. old by two potassium-argon age determinations on biotite.

Quartz diorite has been found by van den Boom and Lahloub¹⁴ in the Jabal al 'Urf area approximately 38 km north-northwest of Al 'Aqabah (type locality) and was mapped also in other places in south Jordan. Pink and gray varieties of granodiorite are extensively exposed in the Wādī al Yitm (Wādī al Yutm) area north of Al 'Aqabah and are the equivalent of the pink granite and gray granite of Ionides and Blake (1939).

Biotite aplite granite is the most common plutonic rock in south Jordan, and is the "granite" of Blanckenhorn (1914), Fuchs (1916), and Blake (1936). Physical age determinations using the potassium-argon method on biotite resulted in ages of 590 ± 20 m.y. (Dr. Snelling, Oxford Univ., 1965, in Bender 1968, p. 20), and 592 ± 10 m.y. and 582 ± 8 m.y. (Lenz and others, 1972). The samples were collected from a roadcut 15 km north of Al 'Aqabah.

Two-mica aplite granites have been identified at long $35^{\circ}12'20''$ E., lat $29^{\circ}45'29''$ N., the type locality in the area of Jabal al 'Urf; alaskite has also been

¹⁴ Boom, Günter van den, and Lahloub, Mahmoud, 1964, Geological and petrological investigations of the igneous rocks in the area of Qawra, south Jordan: German Geol. Mission in Jordan, unpub. rept. (Fed. Rep. Germany Geol. Survey, Hannover.)

identified west of the Ma'an-Al 'Aqabah highway in the area of Wādī al Yitm (van den Boom and Lahloub, 1964¹⁴).

A great variety of dike rocks (fig. 13) intruded

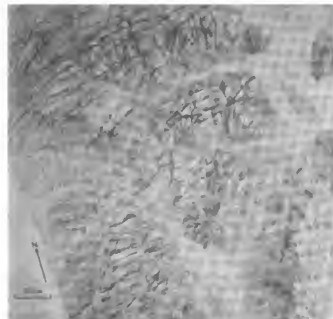


FIGURE 13.—Mafic, intermediate, and silicic dikes in alaskite (southeast and northeast corners of aerial photograph) and in granodiorite and quartz diorite; approximately 15 km west-southwest of Al Quwayrah, southern Jordan.

these plutonites during several phases: quartz dikes, pegmatite, granite-aplite, granite porphyry, quartz porphyry, felsite, quartz-orthoclase porphyry, plagioclase porphyry, kongadiabase (diabase containing quartz), quartz diorite porphyry, orthoclase porphyry, minette, vogesite, kersantite, spessartite, porphyrite, and diabase (van den Boom and Lahloub, 1964¹⁴). The dominant strike directions of these dikes are northeast and east-northeast, and to a lesser degree, east and north. The quantity of dikes decreases with increasing distance eastward from the southern rift zone (Wādī al 'Arabah). None of the dikes, with the exception of some quartz porphyries, invade overlying Cambrian strata.

UPPER PROTEROZOIC SEDIMENTARY ROCKS

The Saramuj Conglomerates (Blanchenhorn, 1912) and the Slate-Graywacke Series (Bender, 1965) overlie and are separated by a profound erosion surface from the plutonic rocks. These units are restricted to local exposures on the east side of the Wādī al 'Arabah-Dead Sea part of the Rift province. The Saramuj Conglomerates consist of

well-rounded boulders and gravel derived from the older igneous magmatites and metamorphic rocks; the conglomerates have a partly brecciated, arkosic sandy cement and alternate with coarse and fine, somewhat arkosic, sandstone beds. They show evidence of slight metamorphism (epizonal metamorphism), and they are greatly faulted and displaced, but no alpine-type folding was observed. In the area of Wādī Abū Barqā (approximately 5.5 km north-northeast of Gharandal) the Saramuj Conglomerates are more than 200 m thick and are conformably overlain by the Slate-Graywacke Series, which is more than 200 m thick. The Slate-Graywacke Series consists of gray-green and red-brown, hard, dense, commonly silicified sandy or silty slates that alternate with subgraywackes. This series is in turn overlain with pronounced angular unconformity by Cambrian sedimentary rocks (fig. 14). Both the Saramuj Conglomerates and the



FIGURE 14.—Angular unconformity between the upper Proterozoic Slate-Graywacke Series and Cambrian sandstone; middle course of Wādī Abū Barqā on the east side of Wādī al 'Arabah.

Slate-Graywacke Series are intruded by numerous dike rocks, such as diabase, porphyrite, and quartz porphyry; only some of the quartz porphyry dikes invade the Cambrian clastic rocks.

UPPER PROTEROZOIC-PALEOZOIC VOLCANIC AND ASSOCIATED ROCKS

North of Gharandal along the east side of the Wādi al 'Arabah part of the Rift province, large masses of irregular stocks and sills and dikes of quartz porphyry and some porphyrite crop out, either within or above the magmatites, within the upper Proterozoic strata, or locally within the Lower Cambrian clastic rocks (fig. 15; Bender, 1965, 1968b).

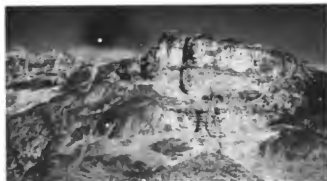


FIGURE 15.—Intrusion of quartz porphyry into Cambrian sandstone; upper course of Wādi Musaymir, east side of central Wādi al 'Arabah.

Ignimbrites and clastic materials in a volcanic matrix were found in the Wādi Abū Khushaybah area approximately 22.5 km north-northeast of Gharandal, at the east side of Wādi al 'Arabah (Bender, 1968b, pl. 14). The age of one such ignimbrite, determined by the potassium-argon whole-rock method, is 471 ± 7 m.y. (Lenz and others, 1972).

From an interpretation of these data and of the mapping results it may be concluded that during the latest Precambrian, quartz porphyry volcanism

took place along the southern part of the Wādi al 'Arabah-Jordan geosuture. These quartz porphyry rocks were subjected to erosion at the beginning of Cambrian sedimentation. Locally, however, volcanism continued while Lower Cambrian clastic rocks were deposited.

POST-PROTEROZOIC STRATIGRAPHY AND VOLCANISM

The lithostratigraphic subdivision of the sedimentary rocks of Jordan, their time-stratigraphic correlation, and the general character of depositional environment are shown on plate 2.

To avoid confusion, the use of the many ill-defined rock-unit and formation names introduced by various authors has been restricted. Instead, lithologic or paleontologic descriptive terms have been used for lithostratigraphic units that have been defined as to their lower and upper contacts, areal extent, and their position in the time-stratigraphic scale.

PALEOZOIC ERA

Cambrian sedimentary rocks are exposed in a belt that extends from the southern end of the country along the east side of Wādi al 'Arabah to the Dead Sea (pl. 1). Cambrian sedimentation started in a continental environment in which basal conglomerates (as much as 50 m thick) were deposited with angular unconformity (fig. 16) above a pronounced erosional hiatus. The conglomerates are only found in the area of the geosuture where they fill in the valleys of a distinct surface cut in the Precambrian basement complex. Conglomerates are absent in the area east of the Wādi al 'Arabah, where bedded arkosic sandstone (as much as 200 m thick) rests on peneplained rocks of Precambrian age (fig. 16).

Above the bedded arkosic sandstone, marine transgressive beds crop out along the east side of the Wādi al 'Arabah between the Dead Sea and Gharandal. Near Gharandal these marine beds are white

Physical age determinations of samples of upper Proterozoic-Paleozoic volcanic and associated rocks

Rock	Location	Age (million years)	Method	Reference
Quartz porphyry mass ---	Jabal at Tayyibah at mouth of Wādi Mūsā into Wādi al 'Arabah.	574 ± 8 -----	K:Ar, whole rock -----	Lenz and others 1972.
Porphyrite mass -----	2 km east of ruins of Faynān (Feinān).	542 ± 8 -----	---do -----	Do.
Quartz porphyry mass ---	Wādi Quşayb -----	530 ± 50 -----	Rb.Sr -----	Dr. Snelling, written commun., 1966.
Quartz porphyry stock in Lower Cambrian sand- stone.	Wādi Musaymir -----	525 ± 10 -----	K:Ar, whole rock ----	Lenz and others 1972.

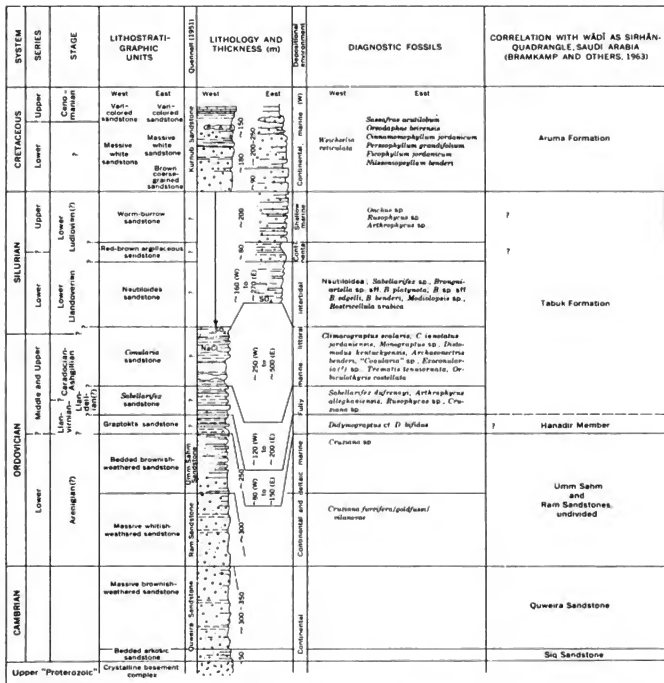


FIGURE 16.—Composite columnar section of Cretaceous and Paleozoic sedimentary rocks in south Jordan.

fine-grained sandstone as much as 110 m thick that interfinger with, and farther south and east are replaced by, the lower part of massive brownish-weathered sandstone of continental origin (fig. 3; altogether as much as 350 m thick; Quweira Sandstone of Quennell, 1951). To the north and west, however, the white fine-grained sandstone is gradually replaced by a marine dolomite-limestone-shale sequence (as much as 50 m thick), which has been known for a long time in the Dead Sea area and has yielded fossils of latest Early to Middle Cambrian age (Blanckenhorn, 1912, p. 129; Diemann, 1915, p. 23-26; King, 1923; Richter and Richter, 1964; Picard, 1942; Wādi Nasb Limestone of Hull, 1886; and Burj Limestone Group of Quennell, 1951, and of Burdon, 1959).

The upper part of the massive brownish-weathered sandstone of southern Jordan also overlies the marine Cambrian beds farther north; in the area east of the Ghawr as Sāfi and the Dead Sea, it is gradually replaced by white bedded sandstone (as much as 220 m thick, Lillich, 1964,¹² 1969), which also may be of marine origin and which is tentatively placed in the Cambrian (pl. 2).

Locally, Ordovician sandstone (fig. 3) crops out conformably above the Cambrian clastic rocks on the east side of Wādi al 'Arabah. In south Jordan east of the Rift province, the Ordovician sequence is more complete, because it dips gently east-northeast underneath Cretaceous strata, that rest upon Paleozoic rocks having a slight angular unconformity.

Massive whitish-weathered sandstone of Ordovician age was deposited in an alternating continental and deltaic-marine environment. The dominantly coarse grained and commonly crossbedded sandstone contains many gravel lenses and scattered quartz pebbles. The sandstone is as much as 300 m thick in the Khawr Ramm-Qā' Dīsh area in south Jordan. Some intercalated silty and micaceous shale yielded well-preserved Early Ordovician (Arenigian?) trace fossils (determined by Huckriede in Bender and Huckriede, 1963). The formation was named Ram Sandstone by Quennell (1951) who considered it to be of continental origin and of any age from Cambrian to Jurassic.

Without visible unconformity, bedded brownish-weathered sandstone approximately 250 m thick lies above the massive whitish-weathered sandstone.

It is exposed only in southern Jordan along a 10- to 15-km-wide belt that extends south-southeast from the escarpment of Ra's an Naqb into Saudi Arabia. The sandstone is poorly sorted and dominantly coarse grained in the lower part, and well sorted and dominantly medium grained in the upper 50-70 m of the formation. It appears dark brown or even black, because of desert varnish; its original colors were pink, beige, gray-brown, and, in the upper part, white. It seems to have been deposited in a near-shore, tidal and in an offshore, shoals environment, and has yielded some traces of fossils (Selley, 1968¹³). The formation is classed as Lower Ordovician because it rests on top of known Lower Ordovician strata and is in turn overlain by fossiliferous sedimentary rocks of Llanvirnian Age. This formation had been named the Umm Sahm Sandstone and assigned to the continental Nubian Sandstone Series of Paleozoic-Triassic-Jurassic age by Quennell (1951).

The Umm Sahm Sandstone is overlain, with a marked lithologic break, by varicolored hard shale, silicified red-brown fine-grained sandstone, and brown well-bedded fine-grained sandstone that alternates with friable sandy shale and siltstone; these beds aggregate approximately 80 m thick. The lower strata of these shallow-water marine fine-grained clastic rocks contain the Llanvirnian (Middle Ordovician) index fossil *Didymograptus* cf. *D. bifidus* (determined by Huckriede, in Bender and Huckriede, 1963). The formation was named graptolite sandstone because it contained the first graptolites discovered in Jordan (Bender and Huckriede, 1963, p. 25). The upper contact was established where sandstone strata full of vertical tubes of *Sabellarifex* overlie greenish friable shale of the graptolite sandstone. The *Sabellarifex* sandstone consists of dominantly fine-grained sandstone alternating with a few sandy shale beds (Bender and Huckriede, 1963, p. 252). It is approximately 120 m thick where exposed west of the Hejaz Railroad. According to the fossil content of the formations below and above it, the *Sabellarifex* sandstone is of Middle Ordovician age (Wolfart, 1968, p. 523).

The *Sabellarifex* sandstone in turn is conformably overlain by marine-littoral fine-grained clastic beds, which contain more silty and fine-grained sandy shale layers than does the *Sabellarifex*; also, these clastic beds locally contain some gypsum and

¹² Lillich, Wolfgang, 1964, Stratigraphical investigations on the Paleozoic and Mesozoic sandstones on the east side of the Dead Sea; German Geol. Mission to Jordan, unpub. rept., Fed. Rep. Germany Geol. Survey, Hannover.

¹³ Selley, R. C., 1968, Sedimentology of the Nubian sandstone in the southern desert of the Hashemite Kingdom of Jordan; Jordan Nat. Res. Authority unpub. interim rept. Jordan Nat. Resources Authority, Amman, Jordan.

rock-salt lenses about 1 cm thick. The lower contact of the clastic beds has been placed at the base of a 12- to 15-m-thick layer of friable greenish sandy shale above *Sabellarifex*-bearing sandstone. This formation was named *Conularia* sandstone for *Ezoconularia* (?) sp. (Bender and Huckriede, 1963) found in the lower third. The *Conularia* sandstone is altogether about 250 m thick, as measured west and east of the Hejaz Railroad between Maḥaṭṭat Baṭn al Ghūl and Al Mudawwarah. This formation has yielded many fossils described in Bender and Huckriede (1963), Huckriede (1967), Bender (1968a), and Wolfart (1968) and can be placed in the Caradocian-Ashgillian-lower Llandoveryan (?).

In southern Jordan east of the Hejaz Railroad, Silurian sandstone and shale conformably overlie the Upper Ordovician. The paleontologic definition of the Ordovician-Silurian boundary is still controversial (Wolfart, 1968). For practical purposes it has been here tentatively placed where the thick marine sequence consisting of the Ordovician graptolite and *Sabellarifex* sandstones and the Upper Ordovician to Lower Silurian (?) *Conularia* sandstone is overlain by the Nautiloidea sandstone (pl. 2; fig. 4, 16). Alternating flaggy fine-grained sandstone and sandy shale beds characterized by many nautiloids overlie the *Conularia* sandstone without a major lithologic break. The Nautiloidea sandstone has yielded many fossils that have been described by Huckriede (Bender and Huckriede, 1963) and Wolfart (1968). This sandstone unit is approximately 160 m thick east of the Hejaz railroad. The total thickness of the whole marine sequence from the Llanvirnian (graptolite sandstone) to the lower Llandoveryan (Nautiloidea sandstone) is thus approximately 560 m. The same sequence is 1,000 m thick or more in Paleozoic sedimentary basins, as indicated by data from drilling operations approximately 20 km northeast of Al Mudawwarah, and by geoelectric and seismic-reflection surveys in the Al Jafr Basin.

Overlying the Nautiloidea sandstone, red-brown argillaceous sandstone approximately 80 m thick is exposed in southeastern Jordan (pl. 1). This formation consists of alternating red-brown coarse-grained sandstone, fine-grained sandstone, and micaceous sandy shale and was most probably deposited in a continental environment. It is placed in the Silurian because of its stratigraphic position in the sequence (fig. 16).

The red-brown argillaceous sandstone is overlain by as much as 200 m of well-stratified, partly crossbedded, dominantly medium- and coarse-grained

gray and light-brown sandstone. Many of these strata are full of worm burrows and tracks of arthropods; some *Onchus* sp., which is a common fossil in the Upper Silurian, have been found (determined by Huckriede, in Bender, 1968a, p. 58) in this worm burrow sandstone.

Devonian sedimentary rocks are not exposed in Jordan, but they may be in the subsurface of the Al Azraq-Wādī as Sirḥān and Al Jafr Basins. Approximately 80 to 120 km southeast of the southeastern corner of Jordan, Lower Devonian beds crop out above the Upper Silurian worm burrow sandstone, in the Al Awi-Al Hūj Mountains in Saudi Arabia (Jafr Formation above Tawil Sandstone Member of Bramkamp and others, 1963). The Lower Devonian there consists of alternating bedded sandstone, sandy shale, fossiliferous impure limestone, algal limestone, and dolomitic limestone, all of shallow-water marine origin and totaling about 200 m in thickness.

Carboniferous beds also are not yet known from exposed sections in Jordan. However, a palynological study (Olexcon Internatl., Ltd., 1967¹⁰) of cutting samples from the Phillips Petroleum Co. SAFRA-1 wildcat oil well (E. W. Pauley Oil Exploration and Phillips Petroleum Co., 1957¹¹) about 42 km east-southeast of 'Ammān revealed spores of early Westfalian A-Namurian-late Viséan Age (Bender, 1968a, p. 213). The spores are in alternating micaceous sandstone and argillaceous sandstone, sandy shale, and impure sandy limestone. Because of the incomplete sampling in SAFRA-1, the thickness of the drilled Carboniferous section is not certainly known; it probably exceeds 200 m.

Permian rocks are not known in exposures or in subsurface sections in Jordan. On the basis of regional stratigraphy in Syria (Weber, 1963), Israel (Gerry, 1967), and Saudi Arabia (Helal, 1964), Permian beds probably will be discovered in the subsurface of the northern and western parts of Jordan.

MESOZOIC ERA

Triassic strata are exposed on the east side of the central Jordan River valley and east of the Dead Sea. They overlie, without visible angular unconformity, the white bedded sandstone that is tentatively placed in the Cambrian (p. 116). Farther east and west of the Jordan River valley, Permian(?), Carboniferous, Devonian(?), and

¹⁰ Olexcon International, Ltd., 1967. Microfossils, palynology, stratigraphy, and oil source rock identification, various wells and sections: The Hague, Netherlands. Olexcon Internatl., Ltd., unpub. rept. for Jordan Nat. Resources Authority.

¹¹ See footnote 9, on p. 12.

Silurian-Ordovician rocks can be expected to be present between Triassic and Cambrian rocks.

On the east side of the central Dead Sea the exposed Triassic rocks consist (from top to bottom) of alternating yellow-brown fine-grained sandstone, sandy marl, and shale (approximately 65 m thick); alternating red-brown, ochre, gray and green shale, argillaceous fine-grained sandstone, and medium- and coarse-grained sandstone (approximately 50 m thick); and alternating red-violet sandy shale and dark-red coarse-grained sandstone (approximately 70 m thick). These Triassic rocks seem to have been deposited in a frequently changing continental (?) to lagoonal and littoral to neritic environment. These sedimentary rocks yield fossils of Scythian Age (Cox, 1924, 1932; Blake, 1936; Wetzel and Morton, 1959; comprehensive list in Bender, 1968a, p. 60-62). To the south, in the area of the lower course of the Wādī al Mawjib, this sequence wedges out between sandstones of Cambrian and Early Cretaceous age (Lillich in Bender, 1968a, p. 59). To the north, however, in the lower Nahr az Zarqā (Zarqa River) the sequence contains gypsum and increases in thickness, and the marine depositional environment is more pronounced than it is on the east side of the central Dead Sea; the sequence here is more than 280 m thick, is of Scythian, Anisian, and Ladinian (?) Age, and includes approximately 70 m "Muschelkalk-facies" (Wagner, 1934). To the west across the Wādī al 'Arabah-Jordan Rift province, the Triassic sequence also increases in thickness to more than 1,000 m in Phillips Petroleum Co. oil exploration well Halhul-1, (E. W. Pauley Oil Exploration and Phillips Petroleum Co., 1958²¹); there the sandy facies is very thin, and limestone, dolomite, marl, and anhydrite are found instead.

Jurassic beds crop out in the areas of the lower course of the Nahr az Zarqā (Zarqa River) to approximately 20 km south of it, on the east side of the Jordan River valley. Farther south, on the east side of the northern Dead Sea, Jurassic beds are absent, and Lower Cretaceous sandstone rests directly on Triassic rocks.

The exposed Jurassic strata consist of (from top to bottom): alternating limestone and sandy marl (220 (?) m thick), plant-fossil-bearing sandstone (as much as 70 m thick), and thick-bedded limestone (as much as 70 m thick). These rocks are of littoral to neritic origin and yield fossils of Bathonian Age (Cox, 1925; Muir-Wood, 1925;

Wetzel and Morton, 1959; van den Boom and Lahlob, 1962²²; comprehensive fossil list in Bender, 1968a, p. 64-67).

The Jurassic sedimentary rocks increase considerably in thickness northward from the outcrop area and westward across the Rift province to more than 2,000 m in the oil exploration well Halhul-1 north of Hebron. There the sequence is of dominantly calcareous-marly, neritic to bathyal facies and probably represents the Aalénian, Bajocian, Bathonian, Callovian, and Oxfordian.

Quennell (1951) and Burdon (1959) classified and described the Jurassic and Triassic rocks in Jordan as the Zarqa Group.

Lower Cretaceous rocks are exposed locally in some structurally elevated areas in west Jordan, and northern Jordan east of the Rift province. They are also found along a belt that parallels the east side of the Dead Sea-Wādī al 'Arabah section of the Rift province, and along the escarpment of Ra's an Naqb in the southeast. They are separated from older sedimentary rocks by a regional depositional hiatus (angular unconformity). Where exposed, the Lower Cretaceous rocks overlie:

1. Oxfordian (?) limestone in west Jordan;
2. Bathonian calcareous sandstone and impure limestone on the east side of the Jordan River valley;
3. Triassic limestone, shale, and sandstone between the northeast corner of the Dead Sea and the Wādī al Mawjib;
4. Silurian sandstone and shale in southeast Jordan;
5. Ordovician sandstone and sandy shale between Ra's an Naqb and the Hejaz Railroad in south Jordan; and
6. Cambrian and remnants of Ordovician sandstone at the east side of Wādī al 'Arabah.

West of the Jordan River-Dead Sea part of the Rift province, varicolored sandstone, argillaceous sandstone, and sandy shale and marl (more than 300 m thick) are of dominantly continental origin and are considered to be Neocomian (equal to the Wādī Hathira Sandstone of Shaw, 1947; or Kurnub Sandstone of Quennell, 1951). Limestone, sandy limestone, and marl of marine origin and of Aptian to Albanian Age form the upper part (more than 80 m thick) of the Lower Cretaceous (Blake, 1936; Wetzel and Morton, 1959). These marine beds increase in thickness toward the western parts of Jordan (Phillips Petroleum Co. oil exploration well

²¹ See footnote 3 on p. 12.

²² Boom, Günter van den, and Lahlob, Mahmoud. 1962. The iron-ore deposit "Warda" in the southern Ajlun district: German Geol. Mission in Jordan, unpub. rept., Fed. Rep. Germany Geol. Survey, Hannover.

Ramallah-1, E. W. Pauley Oil Exploration and Phillips Petroleum Co., 1958²³); they decrease in thickness toward the east across the Jordan River valley. There, only wedges of marine calcareous sandstone (together about 40 m thick) of Aptian-Albian Age (Wetzel and Morton, 1959, p. 138) crop out in the upper part of a section of approximately 170 m of varicolored, coarse-, medium-, and fine-grained sandstone, sandy shale, and sandy marl that commonly contain plant fossils of Neocomian Age (Edwards, 1929).

South from the Dead Sea and southeast along the escarpment of Ra's an Naqb, two units can be distinguished in the Lower Cretaceous sequence—a lower unit of massive white sandstone (as much as 180 m thick), and an upper unit of varicolored sandstone (as much as 150 m thick). Both lithostratigraphic units contain Early Cretaceous plant fragments and are apparently of continental origin. Only the uppermost part of the varicolored sandstone, which is more marly and shaly, shows some marine influence (agglutinate Foraminifera, fish teeth) in the Ra's an Naqb area.

In southeast Jordan, east of the Hejaz Railroad, the massive white sandstone is gradually replaced by brown coarse-grained sandstone (as much as 90 m thick), whereas the varicolored sandstone facies diachronously "migrates" from the Lower Cretaceous into successively younger time-stratigraphic units (Cenomanian, Turonian, Santonian) as one approaches the Nubo-Arabian Shield to the southeast (Bender and Mädlar, 1969).

Upper Cretaceous strata underlie most of the Highlands West of the Rift and most of the northern part of the Mountain Ridge provinces, and they cover almost the entire Central Plateau (pl. 1). The beginning of the Late Cretaceous sedimentation in west, north, and central Jordan is marked by a marine calcareous facies, whereas in southeast Jordan, deposition of sandy sediment continued in a continental environment.

Alternating limestone, dolomitic limestone, marl, shale, locally gypsum, and some chert were deposited on top of the Lower Cretaceous varicolored sandstone. This unit is the nodular limestone member (definitions of Upper Cretaceous lithostratigraphic members given by Bender, 1968a, p. 72-82), which correlates with the lower part of Quennell's (1951) Ajlun Group. It may exceed 450 m in thickness in west Jordan, close to the east side of the rift; in the lower course of the Wādī al Mawjib it was

measured as approximately 300 m, and from there to the south and southeast the thickness decreases to less than 70 m at Ra's an Naqb. On the basis of its abundant fossils, the nodular limestone is assigned to the Cenomanian (Blanckenhorn, 1914). It is succeeded by the echinoid limestone member, which consists of alternating thick- and thin-bedded limestone, dolomitic limestone, marl, and some shale, locally with some gypsum layers; it is equivalent to the middle and upper parts of Quennell's (1951) Ajlun Group. The echinoid limestone member is approximately 210 m thick in the area of the Nahr az Zarqā' (Zarqa River); the thickness may increase to the west and decreases to the south and to the southeast. The upper third shows an increasing sand content south and southeast from the Wādī al Mawjib area. The lower two-thirds of the echinoid limestone member is of Cenomanian Age, its upper third—including its lateral facies equivalent, the sandy limestone member (as much as 110 m thick), south of Wādī al Mawjib—is placed in the Turonian and Santonian.

In north Jordan, the massive limestone member of Santonian Age (as much as 60 m thick) was deposited on top of the echinoid limestone member and is equivalent to the uppermost part of Quennell's (1951) Ajlun Group.

South of 'Ammān, the massive limestone member gradually wedges out, and the succeeding silicified limestone member of Campanian Age directly overlies the echinoid limestone member, or its facies equivalent, the sandy limestone member. Thin-bedded silicified limestone, chert layers, thin more-or-less silicified phosphorite, and thin limestone beds form this mappable lithostratigraphic member (silicified limestone member). It is present everywhere in the country except in the extreme southeast, where it wedges out or, together with the underlying Upper Cretaceous rock units, is replaced by the continental varicolored sandstone. The silicified limestone member is approximately 135 m thick in the Wādī al Mawjib area, but decreases to the west across the Rift province, and 12 km east of Al Khalil (Hebron) it is 20-30 m thick; to the east and to the south at Mabaṭṭat al Hāsā and Al Qatrānah it is 40-70 m thick, and at Zakimat al Hāsā it is less than 20 m thick.

Above the silicified limestone member, the phosphorite member of Campanian and Maestrichtian Age consists of alternating thin-bedded limestone, more-or-less silicified or calcified phosphorite layers, thick-bedded and crossbedded oyster lumachelles, and lenses and layers of minable phosphate. The

²³ See footnote 3 on p. 12.

phosphorite member is approximately 90 m thick close to the Rift province in the Wādī al Mawjib area, and decreases in thickness to the east, to the south, and to the west across the rift.

Both the silicified limestone member and the phosphorite member form the lower part of Quennell's (1951) Belqa Group.

Soft chalk, marl, marly limestone, and locally massive and crystalline limestone (so-called marble) rest (with a marked lithologic break) on top of the phosphorite member. This chalk-marl member, which is equivalent to the upper part of Quennell's (1951) Belqa Group, ranges in thickness from about 20 m in southeast Jordan to more than 450 m as drilled in the Al Jafr Basin. The thick sequence is restricted to basins that strike north-west. Locally in these basins an euxinic facies of bituminous marly limestone exceeds 200 m in thickness, as in the Nahr al Yarmūk (Yarmuk River) area in north Jordan. On the basis of microfossil evidence, the chalk-marl member represents the upper Maestrichtian, Danian, and lower Paleocene, and in addition upper Paleocene and lower Eocene in the sedimentary basins that contain thick deposits of the chalk-marl member.

MESOZOIC VOLCANIC ROCKS

West of the Jordan River, in the Wādī al Mālīb approximately 9 km east of the village of Tūbās, deeply weathered mafic to intermediate eruptive rocks (phonolites, according to Ionides and Blake, 1939) are exposed. They intrude Middle Jurassic limestones, and are, together with tuffs and agglomerates, covered by Lower Cretaceous sandstone. Similar, but smaller outcrops are reported from Wādī al Fāri'ah and near Lūhuf Jadīr west of the Jordan River (Rofe & Raffety Consultant Engineers, 1965²⁴).

Silicic dikes and sills in the Triassic limestones in the area of Wādī Ijībān at the northeast corner of the Dead Sea are mentioned by Quennell (1951, p. 104). At 'Ayn Mūsā of the same area, Wetzel and Morton (1959, p. 124) found trachyte sills and lenses of volcanic ash in the marly sandy beds below and above the Triassic (Muschelkalk) limestones. The age of the dolerite dikes in Wādī al Karak and at several places at the central east side of Wādī al 'Arabāh is yet uncertain; they may have formed during the widespread Pleistocene basalt volcanism.

CENOZOIC ERA

Marine sedimentation during the Late Cretaceous continued without a major lithologic break into the

Tertiary. Sedimentary rocks of Paleocene and Eocene age cover extensive areas in north, north-east, and east-central Jordan; parts west of the Jordan River; and small stretches along the east side of the Wādī al 'Arabāh part of the Rift province (pl. 1).

Massive chalky limestone, alternating thin-bedded limestone and chert layers, and local nummulitic limestone that range in age from early Paleocene to middle Eocene overlie the chalk-marl member. For regional mapping purposes, these sedimentary rocks were described and classified as the chert-limestone member (Bender, 1968a, p. 82-87); it is in part the time equivalent of the upper part of the chalk-marl member that was still being deposited in sedimentary basins where marly and bituminous sedimentation continued into the Eocene. The chert-limestone member is as much as 180 m thick in the Al Azraq-Wādī as Sirḡān sedimentary basin; it decreases in thickness toward south Jordan.

Above the chert-limestone member are the carcharodon marls (more than 50 m thick) and the limestones and cherts of Thuleithuwat (more than 30 m thick) (pl. 2); on the basis of microfossil evidence determined by Wilhelm Koch (in Bender, 1968a, p. 85) these units are of middle Eocene age. They are partly the time equivalent of the barite marls and bituminous marls of Dahikiya (more than 25 m thick), of which the upper part extends into the upper Eocene on the basis of microfossils determined by Koch (in Bender, 1968a, p. 85). These beds crop out locally as erosion remnants in the eastern parts of the Central Plateau; they are probably much thicker in the Al Azraq-Wādī as Sirḡān sedimentary basin.

Oligocene-Miocene strata indicate distinct changes in the depositional environment, which since the Cenomanian had remained marine calcareous over most of Jordan. Glauconitic sandstone, limestone, and sandstone of Oligocene-Miocene age (more than 70 m thick) unconformably overlie upper Eocene rocks in the Al Azraq-Fayḡat aḍ Ḍāhikiyah area, and crop out locally east of the Plateau Basalts in northeast Jordan.

Glauconitic, partly sandy limestone and marl, more than 40 m thick, are exposed in Wādī at Ṭayyibah on the east side of the northern Jordan River valley. They unconformably overlie middle Eocene rocks and are, according to Wetzel and Morton (1959, p. 167), of Oligocene age. In the village of Shūnat Nimrīn in the same area, approximately 40 m of glauconitic and in part sandy limestone is exposed; it probably

²⁴ See footnote 14 on p. 12.

is of Oligocene-Miocene age (Wiesemann and Abdullatif, 1963²⁵).

The lower syntectonic conglomerate unconformably overlies different units of the Upper Cretaceous and the lower Tertiary; it crops out only along the east side of Wādī al 'Arabah and apparently indicates the first major taphrogenic movements of the Jordan rift zone. The lower syntectonic conglomerate consists of alternating conglomerate, sandstone, marl, shale, gypsiferous shale, and some flaky limestone intercalations that total 280 m in thickness in the type-section area approximately 10 km north-northeast of Ash Shawbak (Bender, 1968b, p. 186-188). They contain fossil fresh-water fishes (Cichlidae) and plants (certain Characeae). The plant fossils are thus far known to be restricted to the Rupelian and Tortonian in Europe (determined by Karl Mädlér, in Bender, 1968b, p. 188). The lower syntectonic conglomerate is also locally exposed within the Rift province—for example, at Gharandal in the central part and at Wādī Daḥl in the northern part of the east side of Wādī al 'Arabah. Here, marine influence on the depositional environment is shown in sandy marl layers in the upper part of the lower syntectonic conglomerate; these marl layers contain *Ammonia* aff. *A. beccarii* (Linné), indicative of earliest Miocene (determined by Koch, in Bender, 1968a, p. 88).

The upper syntectonic conglomerate (more than 100 m thick), deposited on an angular unconformity, is mainly a thick-bedded coarse-grained conglomerate that has a sandy calcareous matrix, and overlies the lower syntectonic conglomerate. The upper syntectonic conglomerate is also restricted to the east side of Wādī al 'Arabah; it is of continental origin and probably of late Neogene age.

The upper syntectonic conglomerate may be the time equivalent of the sandy marls and conglomerates (more than 200 m thick) of Adh Dhirā' east of the Al Lisān Peninsula in the Dead Sea (Wetzel and Morton, 1959, p. 169), and of the marine oolitic limestones (more than 40 m thick) from Jabal al Khurayj in the central Wādī al 'Arabah (Bender, 1968a, p. 91).

Also of marine origin and of Miocene age are the sandstone and sandy marl (as much as 40 m thick) of Al Azraq-Fayḍat aḍ Ḍāḡikiyah west and

east of the Plateau Basalt (Baker and Harza Engineering Co., 1968²⁶; Heimbach, 1970).

Restricted to the central and structurally deepest zone of the Rift province are the evaporites of Al Lisān. They were not penetrated in the 3,560-m-deep oil exploration well El Lisān-1; according to a seismic-reflection survey by ARGAS in 1968²⁷, a thickness of approximately 4,000 m can be assumed for this unit. Thus, the evaporites are a major part of the total post-Proterozoic sedimentary column which is on the order of 10,000 m thick beneath the Al Lisān Peninsula. The evaporites consist mainly of halite and a few thin carnallite layers plus some anhydrite, shale, and marl. The shale and marl increase rapidly in thickness toward the east edge of the rift valley, but more gradually toward the south. According to the seismic-reflection survey, it seems that in the southern Ghawr as Sāfi area, approximately 20 km south of the Dead Sea, the salt mass is almost completely replaced by a well-bedded sequence that probably consists of shale and marl. The salt probably represents a "salt cushion" (that is, a gentle doming of the upper surface of the salt bed), which was greatly disturbed at its eastern flank by taphrogenic structural movement, rather than a diapiric salt dome. Palynological studies have revealed that the evaporites are of late Miocene(?) to Pliocene age, and may in part be earliest Pleistocene (determined by Mädlér, in Bender, 1968a, p. 90).

Along the east side of the Jordan River valley, well-cemented coarse-grained clastic rocks alternating with travertines locally overlie older rock sequences unconformably. These clastic rocks, the Shagur Formation (more than 100 m thick), have been strongly deformed by structural movements. They are of continental origin and contain gastropods and ostracodes of late Pliocene to early Pleistocene age (Huckriede, 1966), and thus represent the oldest Quaternary rocks in Jordan.

A sequence of alternating conglomerate, sandstone, marl, shale, and fossil red soil (more than 350 m thick) equivalent to the Series of Grain Sabt (Ionides and Blake, 1939) is exposed in the central Jordan River valley. These rocks are also structurally deformed, but to a lesser degree than is the Shagur Formation. On the basis of rare fossils, the

²⁵ Baker, M., and Harza Engineering Co., 1968, The Princess Alia project—Definite plan report (Azraq), land resources: Baker and Harza Engineering Co., unpub. rept. for the Jordan Government.

²⁷ Arablan Geophysical and Surveying Co. (ARGAS), 1968, Seismic report El Lisān-Chor Sāfi: ARGAS, unpub. rept., Jordan Nat. Resources Authority, Amman, Jordan.

²⁶ Wiesemann, Gerd, and Abdullatif, A., 1963, Geology of the Yarmuk area, north Jordan: German Geol. Mission in Jordan, unpub. rept. Fed. Rep. Germany Geol. Survey, Hannover.

Series of Grain Sabt is tentatively placed in the lower Pleistocene (equivalent to the Ghor el Katar Series of Huckriede, 1966).

Pebble tools of the Oldowan type were discovered by Huckriede (1966) in the gravels of Abū Ḥabīl (more than 10 m thick) on the east side of the central Jordan River valley; Huckriede classed these gravels as middle Pleistocene. He also found early Paleolithic chert implements in the gravels of Kufrinjah, approximately 60 km north of the Dead Sea on the east side of the Jordan River valley.

The Lisan Formation unconformably overlies all older rock sequences in the Rift province. It consists of a lower fossiliferous member, mainly shale and marl (approximately 30 m exposed), and an upper member of varve-bedded marl and shale containing some gypsum and native sulfur (approximately 60 m exposed). The Lisan Formation is of late Pleistocene age and was deposited in a fluctuating oligohaline and miohaline lacustrine environment (Huckriede, 1966). Vita-Finzi (1964) reported upper Pleistocene chert implements from the upper part of the Lisan Formation in the Jordan River valley. At the period of its largest extension, the Lisan Lake covered the entire rift valley from Lake Tiberias to approximately 80 km south of the Dead Sea, a lake some 280 to 300 km long.

Along the margin of the Rift province, the Lisan Formation is intercalated with, or locally replaced by coarse clastic and sandy deposits derived from the elevated areas bordering the rift valley. At other localities close to the shores of the ancient Lisan Lake, a calcareous pseudo-oolitic facies of the Lisan Formation, more than 10 m thick, was deposited—for example, at Khirbat as Samrā' north of Aṛīḥā (Jericho).

Outside the rift valley, fluvial-lacustrine sediments were deposited in barred basins and depressions during the Pleistocene—for example, 1 km east-southeast of Gharandal, west of Maḥaṭtat al Ḥasā and in the Al Jafr and Al Azraq-Wādī as Sirḥān Basins. Fluvial gravels cover extensive areas of the eastern slopes of the Mountain Ridge province and also of the adjacent Central Plateau.

River and wadi gravels, loesslike sediments and aeolian sands, mantle rocks, landslide masses, talus fans, pelitic sediments in mud flats, calcareous sinter, and caliche form the major constituents of the Holocene deposits.

CENOZOIC VOLCANIC ROCKS

During the late Neogene and Pleistocene, basaltic volcanism was widespread in Jordan in the following areas: West of the Jordan River, within the Rift province; along the Mountain Ridge province, along the northwest-striking fracture zones in central and south Jordan; and within the Plateau Basalt province.

West of the Jordan River, basalt is rare, and of lesser areal extent than in Jordan east of the rift. A lava flow covering about 1 km² overlies Eocene limestone approximately 9 km east of Janin. Even smaller extrusions, probably connected with northwest- and east-striking fault zones, were found at 'Anin (approximately 14 km west-northwest of Janin), at Rāfāt (approximately 25 km southwest of Nāblus), and at Sālim.

Within the rift zone, many rather small areas of basalt and tuff were mapped (Bender and others, 1968, Amman sheet) between the Dead Sea and Lake Tiberias; they are absent south of Al Lisān. The basalt flow of Ghawr al Katār approximately 26.5 km north of the Dead Sea unconformably overlies the Series of Grain Sabt (lower Pleistocene) and is in turn overlain by the Lisan Formation. (upper Pleistocene). The basalt flows near the east shore of the northern Dead Sea overlie fluvial gravels that contain implements of the Acheulian. A middle Pleistocene age is therefore assigned to the activity of these volcanoes.

The basaltic rocks along the Mountain Ridge province are restricted to an area approximately 20 km wide and 110 km long between Jabal 'Unayzah in the south and Wādī al Mawjīb in the north. The basalt flows on the upper south side of the Wādī al Mawjīb valley overlie fossil soils and wadi gravels; the basalt lava of Jabal al Qirānah about 5 km northwest of Maḥaṭtat Jurf ad Darāwīsh overlies fluvial gravels of middle Pleistocene age, which yielded many Acheulian implements (Bender, 1968a, p. 99, 105).

Along the northwest-striking Al Karak-Wādī al Fayḥā fracture zone, which extends across the entire Central Plateau for more than 300 km, several isolated basalt flows and basalt and dolerite dikes were observed. The basalts contain many inclusions of the calcareous or siliceous country rock that show traces of superficial melting. The flows also have been found overlying fluvial gravels of middle Pleistocene age. In southern Jordan between Al Quwayrah and Al Mudawwarah, another northwest-striking fracture zone, mainly tension fissures of great vertical extent along which basalt dikes have

intruded, extends for about 70 km through lower Paleozoic sandstone. These basalts contain inclusions of Upper Cretaceous limestone that apparently covered this area at the time the fractures were formed.

The Plateau Basalts of Djebel ed Drouz and Wādī Haurān cover an area of about 45,000 km² (in Jordan about 11,000 km²), and extend from the southern rim of the Damascus Basin in Syria southward into northeast Jordan to the northern rim of the Al Azraq depression. The flows continue for about 210 km southeastward into Saudi Arabia (Al Ḥarraḥ) along the east side of the Al Azraq-Wādī as Sirḥān Basin.

An enormous amount of extrusive rock erupted from many fissures; many vents are still visible as long rows of low cones. Basalt and some tuff also were extruded from clusters of isolated eruption cones. Six different phases of major emissions can be distinguished (van den Boom and Suwwan, 1966, p. 10-20; Bender and others, 1968, El Azraq and H-4 sheets).

The basalt flows of the lower three phases are only known from wells drilled for ground water in the Wādī aḡ Ḥulayl area northeast of 'Ammān (Hunting Tech. Services, Ltd., 1965²¹). These flows are, altogether, as much as 150 m thick in this area and are separated from each other by approximately 5 m of fossil soils, red clays, and fossil weathered basalt surfaces. The uppermost of these three flows is in turn overlain by soils 6 to 20 m thick that are locally covered by a fourth flow which was drilled to a depth of 60 m in Wādī aḡ Ḥulayl. This fourth flow is exposed between oil pump stations H-5 and H-4 and in the area east of Fayḡat aḡ Ḍāḥikīyah; it covers a rather flat surface of older flows or middle and upper Eocene limestones and is locally covered by sandstone, calcareous sandstone, and sandy marl of Miocene age. The eruption of lava flows 1 to 4 can be therefore placed in a time interval which at the earliest started in the late Eocene and at the latest ended in the Miocene.

A fifth flow, which is as much as 25 m thick where exposed but may be much thicker toward the center of the eruptions, is the most extensive flow of the northeast Jordan plateau basalts. This fifth flow covers older flows and Paleogene and Miocene sediments; it can be correlated with the basalts on the limestone plateau of the Nahr al Yarmūk (Yarmuk River) area and has undergone late Pleisto-

cene erosion. The main tuff eruptions started after the extrusion of lava flow 5.

The basalts of the sixth extrusive phase form north-trending flows many kilometers long; as exposed, they are as much as 30 m thick and their surfaces do not show any evidence of weathering. They most probably correlate with the basalts that flowed down the Nahr al Yarmūk (Yarmuk River) valley to the west where they overlie Pleistocene fluvial gravels and fossil landslides. On the basis of archaeological evidence, Picard (1965, p. 359) placed the basalts of the Nahr al Yarmūk (Yarmuk River) valley in the middle Pleistocene. The long rows of low basalt cones, which apparently are fissure effusions, also are part of the sixth eruption phase, because they cross the flows of the fourth and fifth phases. These rows strike east-southeast (azimuth 110°-130°) and were mapped over distances of 90 km (Bender and others, 1968, El Azraq sheet).

The latest eruptions may have continued into historical times, as for example, in some places in the Djebel ed Drouz area in Syria (de Vries and Barendsen, 1954; Burdon, 1959, p. 47).

STRUCTURE

Five major structural provinces may be distinguished according to their structural evolution, types of deformation, and pattern:

1. Wādī al 'Arabāh-Jordan rift,
2. Nubo-Arabian Shield in southern Jordan,
3. Block faults in central and southeastern Jordan,
4. Upwarping, tilting, and block faulting in northern Jordan, and
5. Anticlinorium, upwarping, and block faulting west of the Jordan River.

Wādī al 'ARABAH-JORDAN RIFT

The Wādī al 'Arabāh-Jordan rift forms a section, about 360 km long, of the East African-North Syrian fault system, which is recognizable over a distance of 6,000 km. The Wādī al 'Arabāh-Jordan rift strikes N. 15° E. from the Gulf of Aqaba to the Dead Sea to form the south graben, approximately 200 km long, and turns from there almost due north to Lake Tiberias to form the north graben, approximately 160 km long. The rift separates the Palestine block in the west from the Transjordan block in the east. The width of the graben floor ranges from 5 km to 20 km; most of it is covered by Holocene and Pleistocene fluvial, aeolian, and lacustrine sediments. The southern part of the

²¹ Boom, G. J. van den, and Suwwan, O., 1966, Report on geological and petrological studies of the plateau basalts in northeast Jordan: German Geol. Mission in Jordan, unpub. rept. Fed. Rep. Germany Geol. Survey, Hannover, 42 p.

²² See footnote 11 on p. 12.

Transjordan block regionally dips more steeply northward than does the Palestine block, but the sedimentary column on the northern Palestine block is thicker than that on the northern Transjordan block; therefore, the surface structural position of the Cretaceous-Tertiary sedimentary sequences gradually attains the same level on both sides of the rift valley between the Dead Sea and Lake Tiberias.

The Precambrian structural pattern and the Precambrian joint and dike system as exposed on the east side of the south graben suggest that a structural zone of the weakness (geosuture) or major hinge line already existed here at the end of the Precambrian. Additional evidence is the morphology of the surface of the Precambrian basement complex; this surface is a peneplain some distance east of the south graben, but it is a very irregular surface covered by coarse conglomerates of Early Cambrian age on both sides of the southern part of the present rift valley. (For details on the age and evolution of the Jordan rift, see Bender, 1968b.) Continued tectonic activity along the old zone of weakness is indicated by late Proterozoic to Cambrian quartz porphyry volcanism in the southern Wādī al 'Arabah. Moreover, the presence of a hinge line, or a major paleogeographic divide, is demonstrated by the disposition of the Cambrian sedimentary facies. These facies relations suggest the existence of an elevated Transjordan block east of the southern part of the hinge line which received continental sediments, and a structurally lower Palestine block west of it which contains marine intercalations of Cambrian Age.

Thickness and facies changes in Triassic, Jurassic, Cretaceous, and lower Tertiary sedimentary rocks across the present rift valley indicate the continued mobility of the geosuture.

The taphrogenic structural movements that initiated the formation of the present graben apparently occurred along this preexisting zone of weakness (geosuture) and started during the late Eocene(?)–Oligocene. In the late Oligocene-Miocene, the Transjordan block east of the south graben was structurally elevated and subjected to continental erosion and, locally, to continental deposition (lower and upper syntectonic conglomerates at the east shoulder of the south graben; p. 121). In the graben area itself, marine beds were deposited during the Oligocene and Neogene. The thick evaporite series of late Miocene(?)–Pliocene age in the Dead Sea area demonstrates the gradual decrease and termination of a marine deposition in this part of the graben. Renewed major taphrogenic movements

started in the Pliocene-Pleistocene. These movements continued during several intra-Pleistocene phases and reached another maximum at the time of the wide-spread basalt volcanism of the middle Pleistocene. Further structural movements, though of small scale, are recorded in the upper Pleistocene unconsolidated sediments of the graben.

The post-Proterozoic structural movements in the rift zone, in particular those forming the graben (taphrogeny) since the Oligocene, were of dip-slip type. Only local minor movements of tangential compression and lateral displacement have been observed. Clear evidence of major strike-slip displacements along the rift on the order of 70 km to more than 100 km (Quennell, 1956; Freund, 1965), or evidence of a ramp valley due to east-west compression (Willis, 1928), was not found during geologic mapping by the author.

NUBO-ARABIAN SHIELD IN SOUTHERN JORDAN

The area bordering the northern Gulf of Aqaba, southern Wādī al 'Arabah, and the adjacent area to the east are considered to represent a northern part of the Nubo-Arabian Shield. The shield plunges regionally from there to the north and northeast. As in the southern Negev to the west (de Sitter, 1962), the structural features in this part of south Jordan indicate its cratonic character.

On the east side of Wādī al 'Arabah, southwest-striking graben structures have been mapped where the upper Proterozoic Saramuj Conglomerates and the Slate-Graywacke Series (p. 113) were preserved from erosion prior to Early Cambrian deposition (Bender and others, 1968, Aqaba-Ma'an sheet). Epeirogenic movements affected the Paleozoic strata east of the southern part of Wādī al 'Arabah, resulting in the regional gentle dip of these strata to the north-northeast. The Paleozoic formations were in part eroded before the deposition of Lower Cretaceous clastic rocks. Therefore, from west to east in south Jordan, the Lower Cretaceous rocks overlie, with angular unconformity, progressively younger Paleozoic rock units that range from Cambrian in the west to Upper Silurian in the east.

Taphrogenic movements in the rift area strongly affected the area bordering the rift, chiefly along northwest-, north-, and north-northeast-striking normal faults, antithetic and synthetic fault systems, and narrow long grabens and horsts paralleling the rift.

Approximately northwest-striking tension joints and faults, of little vertical displacement but of con-

siderable length, were traced in south Jordan. The fissures are locally filled by Pleistocene basalts.

BLOCK FAULTS IN CENTRAL AND SOUTHEASTERN JORDAN

Block faults in central and southeastern Jordan are characterized by broad epirogenic swells and basins which dominantly strike northwest and west-northwest: The Al Jafr Basin, Bāyir-Kilwah Swell, and Al Azraq-Wādī as Sirḥān Basin (pl. 3). A pattern of approximately northwest-, approximately north-northeast-, and east-striking normal faults and flexures of minor displacements form in part small horsts and grabens. The northwest-striking fault systems are very long; the Al Karak-Wādī al Fayḥā fault system, for example, is more than 300 km long and apparently is caused by deep tensional forces. In many places, Pleistocene basalts intrude this fault zone. A few small anticlinelike uplifts in central and southeastern Jordan can only be explained as caused by tangential compression (for example, Jabal at Ṭāhūnah, approximately 8 km northwest of Ma'an).

UPWARDING, TILTING, AND BLOCK FAULTING IN NORTHERN JORDAN

In Jordan east of the rift valley between lat 31°30' and 31°50' N., the pattern of dominant block faults characteristic of central and southeast Jordan gradually changes northward into another structural province where tilting becomes a common feature with faulting. This region is called the province of upwarding, tilting, and block faulting. The structures in this area are thought to have been caused by the general change in rock types, the increase in thickness, and correspondingly greater weight of the sedimentary sequence from south to north and northwest; the relatively thin and dominantly competent beds in the south reacted to structural stresses by fracturing and faulting, whereas the thicker and more incompetent beds in the north reacted to the same stresses by arching, tilting, and flexuring. Examples are:

1. The flat broad northwest-striking anticlinal trend of Jabal as Safrā, approximately 42 km east-southeast of 'Ammān,
2. The flat broad upwarp of of 'Ajlūn, about 45 km north-northwest of 'Ammān, which strikes north-northeast for about 25 km and is faulted mainly in its crestral area, and
3. The uplift of Ṣuwaylīḥ approximately 15 km northwest of 'Ammān, which consists of a tilted block that extends southwest for about 12 km. This block rises gently from southeast

to northwest and becomes approximately 4 km wide before it steeply dips northwest along a southwest-striking flexure accentuated by faults.

ANTICLINORIUM, UPWARDING, AND BLOCK FAULTING WEST OF THE JORDAN RIVER

The anticlinorium, upwarding, and block faulting west of the Jordan River are part of a broad arched region that extends to the northern Negev in the south and to Galilaea in the north. The region in general gently dips westward to the Mediterranean Sea, but dips more steeply to the east, before it is abruptly limited by the Jordan rift.

The upwarps of the region are the Negev upwarp in the south, the upwarp west of the Jordan River in the center, and the Galilaean upwarp in the north. Each is a part of the anticlinorium and is subdivided into anticlines and synclines and into tilted blocks commonly limited by flexures. In the Negev upwarp and in the southern part of the upwarp west of the Jordan River, these structures strike mostly northeast, but in the Quseife, Al Khalil (Hebron), Rāmallah, and the Al Buqay'ah anticlines in the central part of the upwarp west of the Jordan River, a north-northeast-striking structural trend becomes dominant. A northwest- and west-northwest-striking fault system in the northern part of the upwarp west of the Jordan River cuts these structural trends, but their north-northeast continuation can be traced in the northernmost part of the upwarp and in the Galilaean upwarp.

ECONOMIC GEOLOGY¹⁰ AQUIFERS

The following major aquifer systems may be distinguished in Jordan:

1. Lower Paleozoic sandstones are important only in the southern and southeastern parts of the country; they receive little direct recharge; ground-water movement is generally east or northeastward.
2. Carboniferous(?), Triassic, and Jurassic sandstones underlie the Cretaceous sandy and calcareous sequences in northern Jordan; depth to these aquifers is more than 400 m in most areas that require ground-water utilization.
3. Cretaceous sandstones may be hydraulically connected with the Jurassic-Triassic systems in the northern part of the country. Owing to intercalated impermeable strata of variable thickness and extent, several aquifers may be

¹⁰ See Note, p. iv.

present within the Cretaceous sandstones at a particular locality. Generally the Cretaceous sandstones are of limited value for economic utilization of ground water because of considerable drilling depths, commonly low permeability, and poor water quality.

4. Cenomanian and Turonian limestones form locally important aquifers mainly in northern Jordan, where they are directly recharged from rainfall on outcrops along the Mountain Ridge east of the Rift.
5. Campanian and Maestrichtian intercalated limestone, silicified limestone, chert, and phosphorite form the most important and extensive aquifer system in Jordan. These Upper Cretaceous rocks crop out in the relatively high rainfall zones along the mountain ridges and highlands east and west of the rift valley, and in large areas they are at depths that can be economically drilled beneath a cover of younger sediments. Ground-water movement generally follows the regional dip away from the rift valley—eastward from the mountain ridges east of the rift, and westward from the highlands west of the rift. However, many of the larger tributaries and side wadis of the Jordan River valley and the Dead Sea cut back into these aquifers and even into deeper aquifers and cause the ground-water to flow toward the rift valley.

An aquifer of local importance is formed by the lower Tertiary chert-limestone member, mainly in the central parts of the Al Jafr and Al Azraq-Wādi as Sirhān Basins.

The chert-limestone member may be hydraulically connected with aquifers in the Neogene sandstone and sandy marl of Al Azraq and with aquifers in the extensive basalt rock sequence of Neogene-Quaternary age north of Al Azraq. Within the rift valley, aquifer systems of local importance are formed by the upper Neogene, upper syntectonic conglomerate, the sands in the Series of Grain Sabt of early Pleistocene age, the coarse clastic intercalations in the Lisan Formation (upper Pleistocene), and the more recent alluvial clastic deposits.

Extensive ground-water investigations were made in Jordan during 1964 through 1969, in particular, by the Food and Agriculture Organization of the United Nations (Parker, 1969; Lloyd, 1969).

OIL AND GAS, BITUMINOUS ROCKS, AND ASPHALT¹¹

For several decades the zone of sedimentary troughs within the unstable shelf area of the Tethys

Sea along the external rim of Taurides-Iranides has been the favored area of intensive and successful oil exploration. Much less exploration was carried out near the northern rim of the Nubo-Arabian Shield because the paleogeography and environment of deposition of the stable shelf area of the Tethys Sea had been considered unfavorable for forming commercial quantities of hydrocarbons. During more recent years, however, petroleum investigations in the Red Sea area, in Israel, and in Jordan have revealed that the stable shelf area of the Tethys Sea contains many more sedimentary basins and swells than had been expected. In some of these basins outside Jordan, oil and gas are now being commercially produced.

In Jordan, new geologic mapping of the entire country has permitted a reinterpretation of the geophysical, petroleum geological, and exploration-drilling results achieved during the periods 1947-49 (Transjordan Petroleum Development Co., Ltd.); 1956-60 (E. W. Pauley Oil Exploration and Phillips Petroleum Co., 6 exploration wells); 1964-66 (J. W. Mecom Oil Co., 3 exploration wells)¹²; and 1968-72 (Industrija Nafta Zagreb Yugoslavia, unpub. data, 1 exploration well). This reinterpretation (Bender, 1969) was substantially supported by recent geophysical and drilling activity for ground-water exploration by the UNFAO "Sandstone Aquifer Project in Southeast Jordan" in cooperation with Jordan's Natural Resources Authority (NRA), since 1964 (unpub. data, 1964-69; Lloyd, 1969; Parker, 1969), and by seismic investigations carried out for NRA by Arabian Geophysical and Surveying Co. (1968)¹³ in 1967-68.

It is thought accordingly that the Wādi al 'Arabah-Jordan Rift, as well as the northwest-striking basins of Al Jafr and Yarmūk-Al Azraq-Wādi as Sirhān (pl. 3), represent zones of repeated structural subsidence and increased sediment accumulation, especially during the Maestrichtian-Danian-Paleogene. A north-northeast-striking sedimentary basin containing a considerably increased thickness of Triassic-Jurassic strata is in the area west of the Jordan River. Oil and (or) gas possibilities may exist in these sedimentary basins, in particular within the transition zones between the stable and the unstable shelf areas of the Tethys Sea. Such prospective areas for oil and (or) gas are:

1. Structural closures and stratigraphic traps in Cretaceous and older reservoir rocks overlying Cretaceous and possibly Jurassic-Triassic

¹¹ See Note, p. iv.

¹² See footnotes 2-4 on p. 12.

¹³ See footnote 27 on p. 121.

source rocks in the Yarmūk-Al Azraq-Wādi Sirhān Basin (total thickness above Precambrian approximately 5,000 m, according to seismic investigations.)

2. Structural closures and stratigraphic traps in lower Tertiary and Cretaceous reservoir rocks below the thick Neogene evaporites or below and in the shale and marl facies equivalents of these evaporites, in the Al Lisān-Ghawr as Ṣāfi area, and in the central part of the Jordan Rift (total thickness of beds above Precambrian approximately 10,000 m, on the basis of seismic investigations.)
3. Structural closures and stratigraphic traps in Lower Cretaceous, Jurassic, and Triassic reservoir rocks, especially those near the southern part of the Jordan-Dead Sea graben (total thickness of beds above Precambrian approximately 5,000 m, on the basis of regional correlations.)

Bituminous rocks are found at different stratigraphic levels in several areas. The highest bitumen contents are in the Upper Cretaceous chalk-marl member (p. 120); the bituminous unit in this member is an euxinic facies deposited in sedimentary subbasins (fig. 17). In the Lajjūn area, Speers¹⁴ (1969) described a deposit of approximately 15 km². The deposit is very uniform in character, and its average yield of shale oil by Fischer assay is 28.1 U.S. gal/ton. Reserves thus far established at Lajjūn are estimated to be about 420 million barrels of shale oil.

Asphalt has been found floating in the Dead Sea and has been collected in small quantities along its shores since ancient times. In 1939, a block of asphalt measuring 150 m³ was salvaged (Ionides and Blake, 1939, p. 122). The asphalt obviously is derived from faults exposed at the sea bottom. A fault breccia impregnated with asphaltic residual oil was observed southeast of Al Lisān Peninsula at the mouth of Wādi 'Isā, where a north-northeast-striking major fault zone separates the echinoid limestone member (Cenomanian-Santonian) from Cambrian shale and sandstone. Because of the small quantities, the asphalt is of no commercial interest.

METALLIC MINERALS

COPPER¹⁵

Copper mineralization is associated with several rock types on the east side of Wādi al 'Arabah be-

tween Gharandal in the south and the Dead Sea in the north (Bender, 1965):

1. In Precambrian mafic dikes; traces, of no commercial interest.
2. In upper Proterozoic-Cambrian quartz porphyries; traces of oxidized disseminated copper ores deserve further investigations.
3. In the Lower Cambrian basal conglomerate; traces, of no commercial interest.
4. In the white fine-grained sandstone of latest Early to Middle Cambrian age.
5. In the dolomite time equivalents of the white fine-grained sandstone.

The mineralized sandstone and dolomite have some possibilities for economic utilization. In the sandstone, the mineralization consists of small ore nodules chiefly of malachite and, very subordinately (in the centers of nodules), of cuprite, chalcocite, bornite, and chalcopyrite. Locally, in the Wādi Abū Khushaybah area, as much as 6 m of the white fine-grained sandstone is mineralized, its copper content averaging 0.53 percent. In places where the mineralization is restricted to thicknesses of only 1.5 m to 0.2 m of the white fine-grained sandstone, the copper content of channel samples ranges from 1.0 to 9.8 percent.

North of Wādi Abū Khushaybah, some lateral equivalents of the white fine-grained sandstone are impure commonly sandy dolomites; the uppermost part of these dolomites is also mineralized, mainly with malachite along fissures and cracks (approximately 0.4 percent Cu over a 1.40-m-thickness of dolomite). Furthermore, pockets of a few tons of high-grade copper ore are found at the top of the dolomites, and in some places the ore extends into the overlying sandstones. This ore consists of planchélite, malachite, and chrysocolla and contains a maximum of 47 percent Cu. These ore pockets are irregular and are sparsely distributed in the dolomites.

The copper mineralization in the sandstone is thought to have been derived from contemporaneous quartz porphyry volcanism during the sandstone deposition (syngenetic), but the mineralization at the contact between dolomite and sandstone is explained by chemical precipitation from descending solutions containing some copper derived from stratigraphically higher sandstones (Bender, 1965).

MANGANESE¹⁶

Manganese ore has been long known from the east side of the northern Wādi al 'Arabah, in the area of Wādi Dīnā. The ore, chiefly pyrolusite, subordin-

¹⁴ Speers, G. C., 1969, El Lajjūn oil shale deposit, Jordan: Jordan Nat. Resources Authority and BP Research Center, unpub. rept., Jordan Nat. Res. Authority, Amman, Jordan.

¹⁵ See Note, p. iv.

¹⁶ See Note, p. iv.

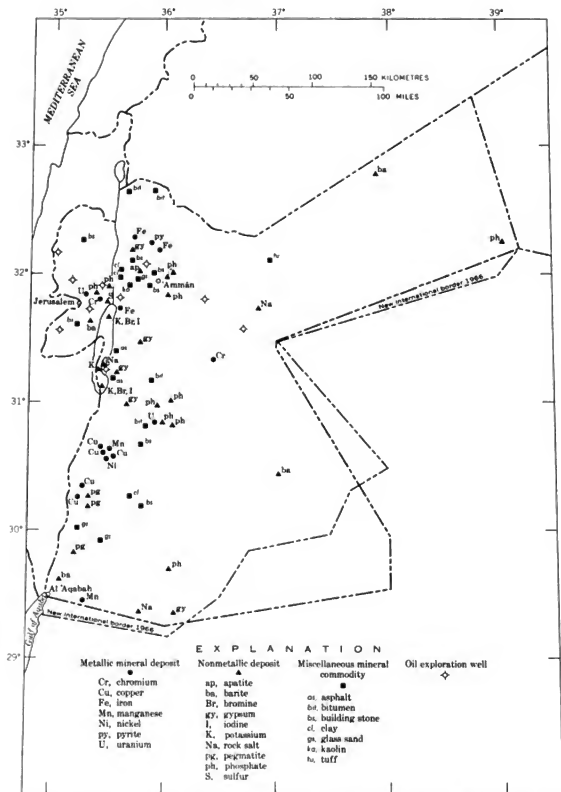


FIGURE 17.—Occurrences and indications of minerals and rocks of economic interest and locations of oil exploration wells in Jordan. (Modified from Bender, 1968a, with the kind permission of the publisher, Gebrüder Borntraeger, Stuttgart.)

ately cryptomelane, ramsdellite, hematite, goethite, malachite, and azurite, consists of nodular masses as much as 3 m thick in the upper part of the dolomite-limestone-shale unit of latest Early to Middle Cambrian age. It is overlain by Cambrian sandstone. Toward the base of the ore zone, shale and sandy shale intercalations increase downward toward the barren part of the sequence. Laterally, the ore thickness may decrease within 200 m, from 3 m to several centimeters thick, but may increase again at other localities; the ore is continuous for many square kilometers in the same stratigraphic interval. The metal content of 36 samples from different localities averaged 33.2 percent Mn and 1.7 percent Cu (Mackay & Schnellmann, 1954²⁷). Van den Boom and Ibrahim (1954)²⁸ mentioned the following metal contents: Mn, between 36.3 and 49.4 percent; Cu, between 1.11 and 2.06 percent; and Fe, between 6.13 and 16.3 percent. According to van den Boom (1969), who gave a detailed description of the manganese ores of Wādī Dīnā, the deposit is of syngenetic origin.

Though 800,000 tons of ore reserves has been proven by exploration work done by the Jordan NRA, the economic feasibility of ore production will be uncertain until processing problems are solved.

IRON

Iron ore was mined in medieval times in the southern 'Ajlūn district, 7 km west of the village of Burmā (about 35 km north-northwest of 'Ammān).

The ore, dominantly hematite and some limonite, forms an irregular lenslike body of metasomatic origin within the massive limestone of Cenomanian-Turonian (?) age (lower part of the echinoid limestone member). Test drilling indicates that the ore body is about 300 m long and 200 m wide and has a maximum thickness of 9.80 m. The average iron oxide content of 205 samples from 15 boreholes was 67.9 percent Fe_2O_3 ; the proven ore reserves are 561,000 tons (van den Boom and Lahlob, 1962²⁹).

CHROMIUM, NICKEL, URANIUM, AND PYRITE

Traces of chromium were described by Blanckenhorn (1912, 1914) from exposures along the Aṛihā (Jericho)-Jerusalem road and also east of the

Jordan River at some localities in the chalk-marl member of late Maestrichtian-early Eocene age (p. 120). Eckhardt and Heimbach (1963) identified a hitherto unknown chromium mineral, chromatite (CaCrO_4), from these outcrops. The chromium is of no economic interest.

Traces of nickel are associated with Precambrian copper-bearing mafic dikes (0.001-0.01 percent Ni), with the copper mineralization of Cambrian sandstones and dolomites (0.001-0.01 percent Ni), with the manganese ores of Wādī Dīnā (0.01-0.1 percent Ni), and with the greenish porphyrite complex east of Faynān (Feinān) at the east side of the northern Wādī al 'Arabah (Bender, 1968a, p. 152). The greenish material of a porphyrite sample contained 0.7 percent Ni.

Several uranium minerals have been found in the phosphorite member and in the overlying chalk-marl member (Maestrichtian-lower Eocene), from exposures in many parts of Jordan; uranophane, tuyamunite, and metatuyamunite were identified by F. J. Eckhardt, Geological Survey, Federal Republic Germany (written commun., 1962). The phosphate rock produced in the Ar Ruṣayfah and in the Maḥaṭṭat al Ḥasā areas contains an average of 100 to 125 ppm U_3O_8 , which corresponds to the world wide average of U_3O_8 content in phosphates (H. Fauth, Geological Survey, Federal Republic Germany, written commun., 1969).

Pyrite is locally abundant in dark shales in the uppermost Lower Cretaceous sequence, approximately 20 to 30 m below the base of the Cenomanian nodular limestone member. No pyrite of economic value is known.

NONMETALLIC MINERALS - PHOSPHATE

Geologic mapping (1:25,000 scale) of all the phosphate-prospective areas in Jordan was done during 1961-66 by the German geological mission. The phosphorite member (pl. 2; fig. 18) could be traced approximately 250 km from the area of Ra's an Naqb in south Jordan to the area north of 'Ammān, and the stratigraphic correlation as well as the structural pattern of the "phosphate belt" was established.

Phosphate deposits of economic interest in Jordan are in the Maestrichtian rock sequence between Maḥaṭṭat al Ḥasā in the south and Suwaylīh northwest of 'Ammān. Here, the Upper Cretaceous formations, which generally have a phosphate content too low to be of commercial value, locally contain lens-

²⁷ See footnote 5 on p. 12.

²⁸ Boom, Günter van den, and Ibrahim, H., 1965, Report on the geology of the Wādī Dīnā area, with special consideration of the manganese-copper occurrences: German Geol. Mission in Jordan, unpub. rept. Fed. Rep. Germany Geol. Survey, Hannover, 95 p.

²⁹ See footnote 22 on p. 118.

³⁰ See Note, p. iv.

like ore bodies or seams of considerable extent and thickness. Because of the regional slight dip of the phosphorite member to the east and the consequent thickening of overburden toward the east, the eastern boundary of the phosphate belt has not yet been defined. Its western border, however, was traced accurately in surface mapping, because the phosphate-bearing strata are uplifted in the west along the mountain ridge east of the rift valley.

In the individual prospective areas (fig. 17), the following observations were made:

1. In southeast Jordan, for example in the area of the village of Iḥaṭṭiya, in the area of Al 'Ināb and northeast and east of the ruins of Kilwāh, phosphorite facies are found in Turonian to Danian-Paleocene-Eocene (?) rocks. The phosphorite facies diachronously "migrates" into successively younger stratigraphic levels from west to east. All phosphate concentrations known in this area are less than 1 m thick and are mostly silicified, calcified, or sandy. No deposit of economic value has yet been discovered in southeast Jordan.
2. In south Jordan (Ra's an Naqb-Ma'ān), some phosphorite occurs in the upper part of the sandy limestone member and in the silicified limestone member (Turonian-Santonian-Campanian; pl. 2). The main phosphorite occurrence, however, is restricted to the phosphorite member (lower Maestrichtian) which is approximately 20 m thick in this area. Quality and quantity of the phosphate ores are below the margin for commercial production in this part of south Jordan.
3. In the Maḥaṭṭat al Iḥṣān-Al Qaṭrānāh area, the phosphorite member (Maestrichtian) increases in thickness to about 40 m. Mostly in its lower third, but also in its upper part, several phosphate-rich layers and lenses are separated from each other by limestone, marl, and chert. Locally the high-grade ore lenses are as much as 10 m thick (fig. 19). The minable phosphorite in the individual lenses ranges from 1 million to 15 million tons. So far, approximately 53 million tons of ore containing more than 67 percent tricalcium phosphate has been proven in this area.
4. Between Al Qaṭrānāh and 'Ammān, other promising phosphorite layers were located during geologic mapping, but as yet have not been prospected sufficiently to justify reserve calculations.

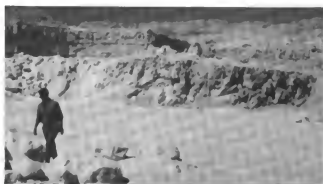


FIGURE 19.—Phosphate in open-pit mine at Maḥaṭṭat al Ḥasā; ore body of Old Concession in central part of photograph approximately 5 m thick.

5. Approximately 15 km northeast of 'Ammān are the well-known and commercially productive phosphate deposits of Ar Ruṣayfah. The four layers that are mined are more constant in thickness than are the ore-bearing layers farther south. At Ar Ruṣayfah, the ore-bearing phosphorite member is about 30 m thick and is of Maestrichtian Age. About 39 million tons of phosphate ore containing more than 62 percent tricalcium phosphate have been proved in the Ar Ruṣayfah area.
6. North of Ar Ruṣayfah-'Ammān, no phosphate deposits of economic value are known.
7. In the area west of the Jordan River the phosphorite member is 25–35 m thick, but the phosphate beds are very impure and thin. The phosphorite member in this area is probably of Campanian Age.
8. In northeast Jordan, impure and thin phosphorite layers were discovered in the lower Tertiary, about 70 km south of the Baghdad road, close to the Jordan-Iraq border (fig. 17). These phosphorites have not yet been investigated in detail.

OTHER MINERALS*

About 16 km northwest of 'Ammān, the phosphorite member crops out in a steep, partly overturned flexure. Here, most of the phosphorite is altered to hard, dense, gray-greenish and red apatite. The reserves of apatite ore are estimated to be 900,000 tons. The average tricalcium phosphate content is about 70 percent. The results of a detailed geologic study of this the only apatite deposit in Jordan, have been published by Wiesemann and Rösch (1969).

* See Note, p. iv.

Barite is present 10 km east-southeast of Bayt Sāhūr (west of the Jordan River) as an irregular mass in limestone and marl of Turonian(?)–Santonian Age. It also fills dikes as much as 0.60 m thick in the lower Eocene calcareous beds of north-east Jordan, 46 km northwest of oil pumping station H-4. Other thin barite dikes were found in major fault zones on the east side of southern and central Wādī al 'Arabah. In the crest of an anticlinal structure at Zakimat al Ḥasā, 52 km southeast of Bāyir, barite rosettes were observed in the varicolored sandstone of Early Cretaceous–Cenomanian Age. Commercial production on a small scale may be possible from the irregular mass near Bayt Sāhūr and from the dikes in northeast Jordan.

Feldspar and mica are common in the Precambrian igneous rock complex, but their quality and quantity do not justify production. Orthoclase or potassium feldspar might eventually be produced by processing the pegmatitic granites near Al Quwayrah.

Quartz forms the main constituent of many pegmatite dikes in the igneous basement complex, in particular along the east side of central and southern Wādī al 'Arabah. In most places, however, the quartz is too impure and disseminated for any commercial use.

Glass sands of good quality and of practically unlimited quantity have been observed in the lower part of the Lower Cretaceous massive white sandstone unit, and in the massive whitish-weathered sandstone unit of Early Ordovician age. Suitable exposures for glass sand production from both of these stratigraphic units are in the area of Qā 'Disah in southern Jordan, at several places along the highway crossing the escarpment of Ra's an Naqb, in the Wādī as Siq approximately 7 km east-southeast of Gharandal, and near the road between Nā'ūr and Ash Shāgūr.

Agate and rock crystals (quartz) are occasionally found in vugs, concretions, and fillings of joints in the silicified limestone member (Campanian), and in the chert-limestone member (lower Eocene)—for example, along the outcrop belt of these rocks between Ra's an Naqb and Al Quatrānah, near Maḥaṭṭat Baṭn al Ghūl, and approximately 20 km southeast of Bī'r an Na'ām in southeast Jordan. These occurrences are of no economic importance.

Garnet was discovered in gravels and sands of the Wādī Abū Barqā and Wādī Hūwar (7 km and 17.5 km north-northeast of Gharandal) on the east side of the Wādī al 'Arabah, and in biotite-garnet schists exposed along the middle course of Wādī

Abū Barqā, as well as at the part of Wādī Hūwar south of Jabal al Muraybid. Because of the impure quality of the garnets and because of the small quantities so far located, they can hardly be considered as having any commercial value.

Semiprecious stones such as malachite, chrysocolla, and planchéite, are constituents of the epigenetic copper ores in the Cambrian dolomite-sandstone complex (p. 127), in the area of Faynān on the east side of the northern Wādī al 'Arabah. Cutting and polishing tests have shown that these minerals are suitable for gem-stone manufacture. Pockets and lenses of as much as 1 ton of malachite, chrysocolla, and planchéite were found during geologic mapping (Bender, 1965, p. 196).

Gypsum forms beds 1–4 m thick in the middle part of the Cenomanian nodular limestone member in the Wādī al Karak, and in the lower third of the echinoid limestone member (Cenomanian–Turonian) at the northern slope of Wādī al Mawjib. Gypsum is also exposed about 35 km northwest of 'Ammān, at the mouth of Wādī al Hūnah into the Nahr az Zarqā River, in a 25-m-thick part of the Triassic rock sequence. These occurrences could be eventually of commercial value, but thin gypsum layers in the chalk-marl member (Maestrichtian–Danian), and gypsum lamina and gypsum concretions in the Lisan Formation are of no economic interest.

Several layers of anhydrite were penetrated in the wildcat oil wells SAFRA-1 (E. W. Pauley Oil Exploration and Phillips Petroleum Co., 1957⁴²) in Lower Cretaceous(?), Jurassic, and Triassic rocks; anhydrite was also in the Miocene(?)–Pliocene evaporite sequence in El Lisan-1 (E. W. Pauley Oil Exploration and Phillips Petroleum Co., 1960⁴³), and in other wells on the Al Lisān Peninsula in the Dead Sea (Jordan Natural Resources Authority, unpub. data, 1967, 1968).

Rock salt is produced in small quantities in the area of the Al Azraq Basin, where saline ground water is collected in trenches and brought into evaporation pans.

The almost unlimited reserves of rock salt that underlie about 100 m of upper Pleistocene marls on the Al Lisān Peninsula in the Dead Sea have not been utilized as yet.

The amount of rock salt dissolved in the Dead Sea is estimated to be approximately 12,650 million tons. Because of impurities, in particular the magnesium salts, rock salt cannot be produced by simple evaporation of the sea water.

⁴² See footnote 3 on p. 12.

Potash and magnesium salts are also dissolved in huge quantities in the Dead Sea water. The total amount of dissolved KCl is calculated to be about 2 billion tons, and the amount of $MgCl_2$ is about 23 billion tons (Bentor, 1961). In the total water volume (143 km³) of the Dead Sea, the dissolved bromine salts amount to 975 million tons $MgBr_2$, and the rubidium salts amount to 12 million tons $RbCl$ (Bentor, 1961).

Potash layers were first discovered in the El Lisan NRA-1 well (Jordan NRA, unpub. data, 1967), which penetrated a part of the Miocene(?)–Pliocene evaporite sequence at the southeast side of the Al Lisān Peninsula (Bender, 1969, p. 602). Little is yet known about the extent of these potash layers.

Native sulfur is widespread in the upper Pleistocene Lisan Formation; the formation can be traced in the rift valley from the north shore of the Dead Sea for more than 40 km to the north. The sulfur occurs as finely crystalline coatings on joints and fault planes, along bedding planes, and in small pockets within gypsum concretions. Paper-thin layers of amorphous sulfur are locally interbedded with the alternating, varvelike shales and marls. Variable quantities of amorphous sulfur nodules 0.5–10 cm in diameter cover the bedding planes in parts of the Lisan Formation. The distribution of sulfur is very irregular, and no place has yet been discovered where commercial sulfur production from the Lisan Formation would be justified.

Ochre and amber occur at several places within sandy gypsiferous lacustrine sediments of middle(?) Pleistocene age on the plateau of Lower Cretaceous sandstones at Jjumrat Mā'in, north of Wādī Zarqā' Mā'ayn. These raw materials for pigment consist of small irregular lenses as much as 1 m thick of yellow ochre and of dark-brown to black, impure, earthy manganese ore containing gypsum. It is not known whether these pigments are suitable for commercial use.

Clay deposits of commercial value crop out locally in northern Jordan within the massive white sandstone unit of Early Cretaceous age. At Ghawr Kabid on the east side of the Jordan River valley, a clay bed 0.40–6.0 m thick is exposed which has an aluminum content of 32.8–37.6 percent; the proven reserves are 47,000 tons. In the area of Māḥiṣ, a similar deposit of about 46,000 tons of clay is exposed.

Substantial parts of the nodular limestone member (Cenomanian) meet the requirements of raw material for cement (25–60 percent carbonates, 40–75 percent noncarbonates). Portland cement is be-

ing produced from this rock unit near Al Fuḥayṣ, north of 'Ammān.

Tuff is found in volcanic cones and as thin sheets in the basalt area in northeast Jordan. It has been produced for many years from Jabal ar Rutayn east of Al Mafrāq, mainly for lightweight concrete, for thermal-insulation material, and for roadmaking material. The tuff reserves are sufficient for commercial production at a much bigger scale than at present.

Only a few examples of the multitude of building stones used since ancient times in Jordan will be mentioned here:

1. Oolitic limestone of Pleistocene age exposed in the western Jordan River, near Kirbat as Samrā'.
2. Thick and hard caliche (referred to as "Nari" in Jordan) of Quaternary age, in the area of Jarash.
3. Massive oyster-shell limestones of the phosphorite member of Campanian-Maestrichtian Age, in the area between 'Ammān and Al Qatrānah.
4. Greenish, reddish, light-pink, and white limestones of different units of Turonian to Maestrichtian Age west of the Jordan River, particularly in the vicinity of Jerusalem and Bethlehem.
5. Reddish, pink, beige, and light-gray limestones in the upper part of the echinoid limestone member and in the massive limestone member of Turonian-Santonian Age, which are extensively quarried in and near 'Ammān and at many other localities in north Jordan.

Well qualified as decoration stones are hornblende gabbro, quartz diorite, granodiorite, and, locally, quartz porphyry, as exposed at many places on the east side of Wādī al 'Arabah and in the area of Al Quwayrah in southern Jordan.

The rocks quarried and sold as marble in Jordan are actually polishable limestones. They are only slightly recrystallized, hard and dense, and are heavily jointed and fissured. These limestones are variously colored by iron compounds, bituminous matter, apatite and traces of chromium-, nickel-, vanadium-, and uranium-bearing minerals. The limestones are present locally in the upper part of the chalk-marl member of latest Cretaceous to early Tertiary age, and are extensively quarried east and west of the desert highway between Al Jizah and Al Qatrānah, particularly in the area of Qasr el Ḥammām.

The lower Pleistocene travertine of the Shagur

Formation can be considered as a valuable building and decoration stone, which so far has not been utilized in Jordan. At several places along the east side of the Jordan River valley the travertine is suitable for quarrying. Approximately 10 km south of Dayr 'Allā, extensive outcrops almost parallel-bedded travertines as much as 10 m thick were observed.

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